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IMPROVED UTILIZATION OF LUMBER IN GLUED LAMINATED BEAMS.(U)

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Abstract

Evaluation of 120 glued laminated (glulam) beams provided criteria for improved utilization of lumber in such beams. Objectives were: (1) to determine if lumber grade can be somewhat reduced on the compression side of beams without significantly changing design strength; (2) to establish analytic procedures for incorporating lumber having had its modulus of elasticity (E) determined (E-rated lumber) into glulam beams; and (3) to determine the effect on beam properties of using lumber with limited wane.

Test results indicated that wane of up to 1/6 of the lumber width along either or both edges did not result in large shear weaknesses; thus design levels in shear equal to 2/3 that of wane-free lumber appear justified. In addition, a design procedure was developed for reducing grade of lumber in the compression side of glulam beams. Such use of lower grade material was not found to change the breaking level of near minimum strength beams. Testing was also done of E-rated lumber in glulam combinations. Procedures for incorporating E-rated lumber into beams are presented so that results will be in line with those for beams made entirely of visually graded lumber.

The procedures developed will provide those preparing specifications a wider raw material base for glulam timber, resulting in more efficient use of our timber resource.

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Acknowledgment

Many members of the staff of the U.S. Forest Products Laboratory contributed to this study. R. Wolfe assisted in beam manufacture and also helped reduce and analyze the data. K. Kanvik assisted in beam manufacture and supervised the testing. J. Lengel and J. Haskell conducted analyses on the knot and strength data; R. Gillespie and R. Jokerst studied failure in finger joints; and R. Koeppen made anatomical identification of wood species in certain beam groups. Testing was conducted by R. Geier, J. Wood, E. Geske, and J. Hillis.

In addition, Paul Nicholas of the American Institute of Timber Construction arranged for all lumber procurement and beam manufacture. And S. K. Suddarth of Purdue University is acknowledged for help in presenting the design approach for unsymmetric beams.

IMPROVED UTILIZATION OF LUMBER IN GLUED LAMINATED BEAMS[1/]

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INTRODUCTION

Efficient utilization of America's forest resources must be a primary concern of all forestry-oriented research if the Nation's needs for wood are to be met in the future. Revised design of glued laminated (glulam) beams may permit lower grade materials to be used without seriously affecting the design strength, thus extending national supplies of high-grade lumber materials.

A design concept to estimate bending properties for glulam beams from mixed species and different lumber grades, developed at the U.S. Forest Products Laboratory (FPL), was published in 1974 (15).[3/] That approach used transformed section analysis, the I_K/I_G concept, and tension lamination requirements to predict near minimum bending strength and average stiffness.

Three approaches to conserving lumber in beams, not investigated in the 1974 study (15), are explored here: (a) reducing grade of lumber on the compression side of beams; (b) using lumber with wane for inner lamination; and (c) extending criteria developed for visually graded lumber to lumber which has had its modulus of elasticity (E) determined (E-rated lumber). The present study has extended criteria developed in (15) to unsymmetric glulam beams using visually graded or a combination of E-rated and visually graded lumber. Criteria were evaluated by tests of 12- or 18-in.-deep beams designed to fail first in compression or to have near equal likelihood of failing in either tension or compression. In addition, the effect of introducing limited wane in the interior laminations was evaluated by subjecting beams containing such material to high shear stresses during tests.

Compression Side Overdesign

Beams designed by both the original I_K/I_G concept and the concept as modified with transformed section analysis will generally fail in tension, not compression. Glulam beams are usually overdesigned in compression; this was noted by Moe (14) and Madsen (13), and has been verified since by test results at various laboratories (8,12,15,19). The current standard AITC 117-74 (1) recognizes compression overdesign in that lamination grades are lower for the compression than for the tension side. The basis for AITC 117-74 is an averaging approach with the I_K/I_G concept. However, derivation of these combinations does not consider a shift in the neutral axis due to the unbalanced design.

To compensate for compression overdesign, higher clear wood stress values may be assumed for the compression side than for the tension side. Bohannan's study of prestressing (7) indicates how much higher the compressive stress could be. He found that 1,300 lb/in.^{2} prestress on the compression side induced a significant number of compression failures in tests of L3 grade Douglas-fir lumber. If this, 1,300 lb/in.^{2} value is added to the 6,350 lb/in.^{2} clear wood design stress value for Douglas-fir (appendix I), an increase of approximately 20 pct in clear wood stress for the compression side is indicated. This

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1/ Research conducted in cooperation with the American Institute of Timber Construction.

2/ Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

3/ Underlined numbers in parentheses refer to literature cited at end of this report.

procedure interprets the 1,300 lb/in.2 value as an increased strength capability for the compression side. This increase will probably not be valid for clear lumber because small clear beams will usually fail in compression, but it should be valid for structural beams.

Analysis of data from three studies—FPL 236 *(15)* and two test series conducted by Johnson *(8,9)*—indicates that if this 20 pct value is applied on the compression side in all cases, no beam strengths will fall below the calculated strength levels. One of the goals of the present study has been to determine the amount that the clear wood stress for the compression side of glulam timbers might be increased for various structural grades of lumber.

Using E-Rated Lumber

Since the development of mechanical stress rating systems, one promising area of application frequently discussed has been glulam timber *(9)*. Such a system might be used to select high-grade lumber for outer laminations and lower grade for the inner, less stressed lamination. Koch et al, *(11)*, working with veneer and thin lumber, demonstrated its potential.

Aplin *(6)* considered utilizing E-rating for manufacturing glulam beams using structural spruce lumber from Eastern Canada. He concluded from tests of 32 beams that strength and stiffness levels higher than with visually graded material were possible. However, he noted that stiffness grading alone was not sufficient and recommended additional visual assessment of each board. Subsequent work on five southern pine beams confirms the potential but also suggests the need for visual assessment, at least for the highly stressed tension zone material *(16)*.

Based on tests conducted by Johnson *(8,9)*, an AITC Standard was developed on the use of E-rated lumber for glulam beams—AITC 120-71 *(2)*. Unfortunately, the combinations are limited to only those evaluated, and any variation from the standard must be supported by further testing.

The promise of E-rating combined with proof loading is further confirmed by Strickler and Pellerin (for one example see *(21)*). Also, Littleford *(12)* has noted that E-rating offers potential for developing design stresses 30 pct higher than with visual grading alone for spruce and pine in Western Canada.

We believe that the modified I_K/I_G concept developed in *(15)* can be applied to combinations in AITC 120-71 as a theoretical mechanism for studying variations. This standard assumes balanced stiffness combinations, and test results verify that the lower strength beams will fail in tension, not compression. A variation on this standard introducing unbalanced E grades may increase the probability of compression side failures and approach a "balanced strength" design. We believe that failures of this type will result in less variable strength data and more efficient use of material when strength is the principal design limitation.

Lumber with Wane

Wane is not permitted in current lumber grades for laminating, which eliminates much otherwise acceptable material. This restriction assures a full-width gluing surface to develop shear strength in the beams. However, by permitting limited wane and reducing the design level in shear, satisfactory beams for dry uses may be obtained.

Effect of wane on the shear strength of glulam beams will be assumed to depend on the amount of wane present. For members subjected to continuous dry use, wane of up to one-sixth of the lumber width at each edge will be assumed to reduce shear strength by up to one-third (i.e., reduced proportional to the maximum shear area lost due to wane). Note: permitting uncontrolled wane along one edge in amounts larger than this is not directly comparable.

Wane may introduce problems due to stress concentrations at the gluelines in beams subjected to repeated wetting and drying. Such exposure, until thoroughly researched, is not recommended; beams made with wany lumber are proposed for dry use only.

DEVELOPMENT OF DESIGN CRITERIA

Design criteria in (15) are limited in several respects. They neither account for compression overdesign nor provide for use of E-rated lumber. In the present study, the criteria presented in (15) were modified to analyze unsymmetric beams by considering the neutral axis shift.

Many changes are necessitated by the neutral axis shift and, initially, its position must be determined from the transformed section (figs. 1a and 1b).

$$z = \frac{\sum_{n=1}^{N} A_n y_n}{\sum_{n=1}^{N} A_n} \qquad (1)$$

where A is the cross-sectional area of the lamination and where y is the distance from the base to the centroid of the different areas. Once the neutral axis is positioned, the beam stiffness can be determined as

$$EI = \sum_{n=1}^{N} E_n I_n \qquad (2)$$

Compression and tension zones of the beam are thus defined and stresses can be determined by independent analysis of each zone as half of a symmetrical beam (figs. 1d and 1e). Stress capabilities at each change in stiffness of the cross section, f_n, can then be determined following procedures given in appendix I of (15).

Changes in notation from (15) are necessary because of the change in method of designating zone depths. For the tension zone, n_1 becomes $2z$, n_2 becomes $2(z - d_1)$, and n_3 becomes $2(z - d_1 - d_2)$. For the compression zone, n_1 becomes $2(d - z)$ while n_2 becomes $2(d - z - d_4)$. Also, for the compression zone the subscript notation must be modified in terms of whether zones 3 or 4 are being considered.

The procedure for checking inner lamination overstress also changes to the following:

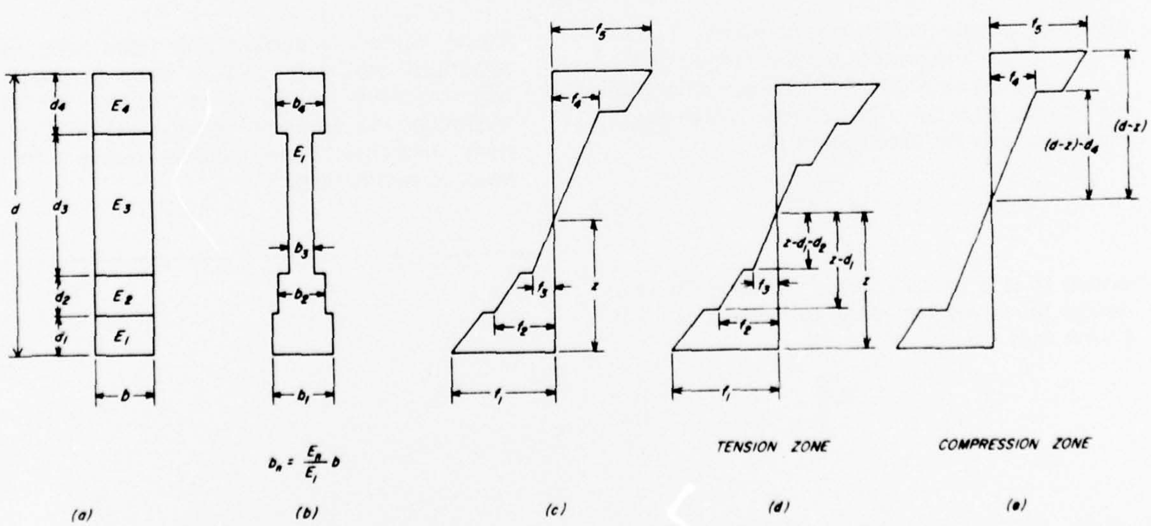


Figure 1.—Transformed section showing stress distribution within a beam having four stiffness zones.
(M 145 167)

$$f_2 > \frac{(z - d_1)E_2}{z \quad E_1} f_1 \qquad (3)$$

$$f_3 > \frac{(z - d_1 - d_2)E_3}{z \quad E_1} f_1 \qquad (4)$$

$$f_4 > \frac{(d - z - d_4)E_4}{z \quad E_1} f_1 \qquad (5)$$

$$f_5 > \frac{(d - z)E_5}{z \quad E_1} f_1 \qquad (6)$$

If these inequalities are not satisfied, f_1 is limited to a value that will satisfy an equality.

For design use, the bending moment capacity should be determined using easily measured quantities; probably the most feasible are the physical dimensions. The conversion to readily usable stress values is best made by utilizing a transformed section factor T, defined as the ratio of the transformed moment of inertia of the cross section (fig. 1 b) to the actual value (fig. 1 a). For unbalanced combinations,

$$T = \frac{I_1}{I} \qquad (7)$$

Where I_1 is calculated from figure 1b,
T is transformed section factor, and
I is moment of inertia based on actual dimension (fig. la). The stress value, f_1 in figure 1c, can be determined as:

$$f_1 = \frac{Mz}{I_1} \qquad (8)$$

where M is a given applied moment. But for design purposes it is useful to define a value of f such that

$$f = \frac{M\frac{d}{2}}{I} = \frac{M}{S} \qquad (9)$$

where d is the beam depth and S is the section modulus. By solving both equations (8) and (9) for M and equating, it can be shown that

$$f = \frac{f_1 I_1 d}{2zI} = f_1 \left(\frac{Td}{2z}\right) \qquad (10)$$

Also, because E_1I_1 - EI,

$$E = E_1T \qquad (11)$$

E-Rated Lumber

To extend the developed I_K/I_G concept to E-rated lumber, it was necessary to develop clear wood stress (CWS) values and knot properties for the respective grades. If these values are known, the different E grades can be treated much the same way as species might be for visually graded lumber. Using the beam strength data presented by Johnson *(8, 9)* and, in addition, supplemental unpublished knot information, the following CWS values were estimated for various grades:

Nominal E-grade	Estimated near-minimum ultimate CWS Lb/in.^{2}
1.4	4,200
1.6	5,250
1.8	6,300
2.0	7,350
2.2	8,400

These values, if correct and used with appropriate knot data, can be used to predict near-minimum modulus of rupture (MOR) values for the 5-min laboratory test of 12-in.-deep uniformly loaded beams having a 21:1 span-to-depth ratio.

Beam Design and Manufacture

Eight different beam combinations were designed—four having all visually graded lumber and four having the outer few laminations both E-rated and visually graded while the inner laminations were visually graded only. Six of the eight combinations were 12 in. deep. The other two had lumber with wane in the inner laminations; they were made 18 in. deep to impose high shear stresses on these inner laminations during test. Four combinations utilized E-rated lumber but the compression side laminations all had large knots characteristic of the inner laminations.

The eight combinations were all of nominal 2- by 4-in. lumber, and all were of unbalanced design, having lower grade material on the compression side. Fifteen replicates were evaluated for each beam group. Species and grades of lumber, along with the arrangement of lamina, are illustrated in figure 2 for all groups. Estimated strength values for these beams, calculated using the developed design concept, are presented in table 1 and figure 3. In addition, assumed lumber properties are given in appendix I and detailed information on source and properties of materials in appendix II.

Beams of Visually Graded Lumber

Group A beams incorporated four Douglas-fir outer laminations and five Engelmann spruce inner laminations; Engelmann spruce is a near-minimum strength and stiffness species included in the western or white wood group *(23,24)*. These inner laminations were lower grade than commonly used for laminating with western species. Instead of an L3 structural lamination, it was No. 3 structural light framing as deter-

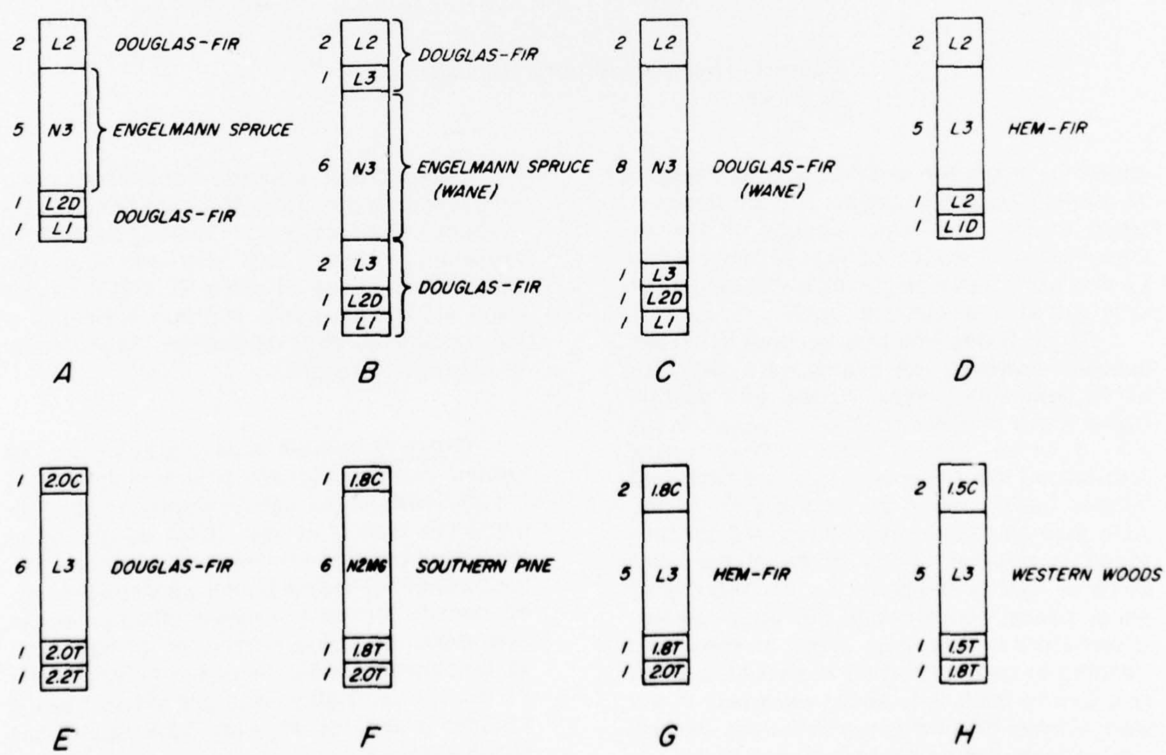
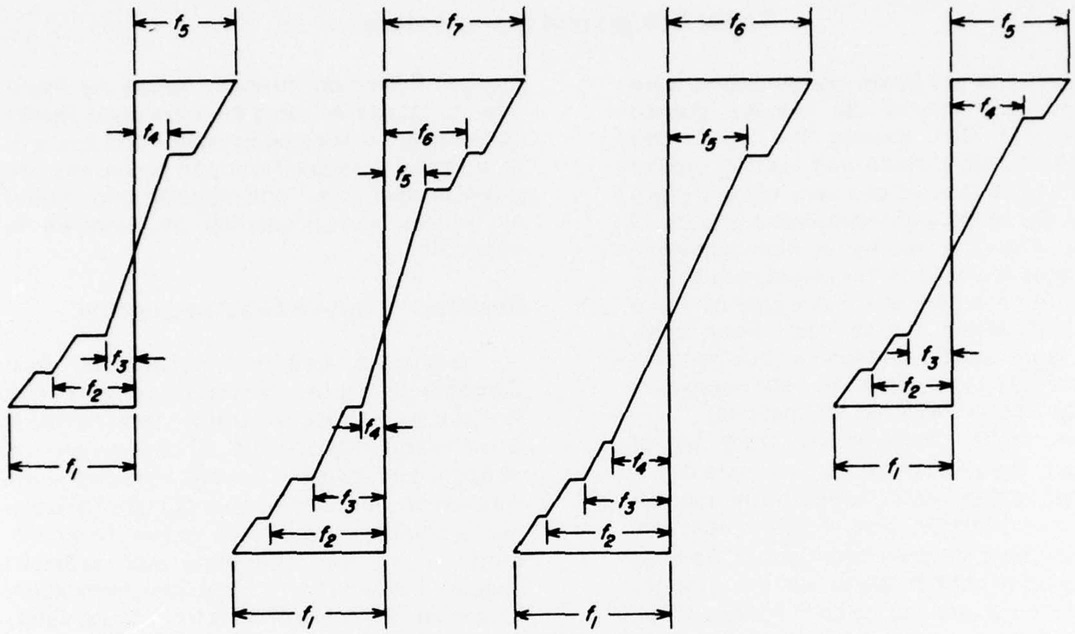


Figure 2.—Diagram showing composition of beam combinations evaluated.
(M 145 171)



A,D,G,H B C E,F

Figure 3.—Beam stresses referenced in table 1.
(M 145 168)

mined by a grader certified by the Western Wood Products Association and a representative of the American Institute of Timber Construction. The main difference between the L3 and No. 3 was a larger allowable centerline knot and steeper slope-of-grain.

Group B was similar to group A in lumber species. However, the beams were designed as 13 laminations deep instead of 9 so that higher shear stresses could be imposed on the No. 3 inner laminations. These inner laminations were specially selected such that lumber having wane up to one-sixth of the wide face on one or both edges was concentrated in one-half of the length of the inner three or four laminations (fig. 4). The higher shear stress, coupled with the wany lumber, allowed probable design levels in shear and bending to be approached at about the same rate during tests. Any shear weakness in the wany lumber beyond assumed values was expected to become apparent during tests.

Group C also explored the effect of wane on shear strength, but in this case the wany inner laminations were of No. 3 Douglas-fir. This material is stiffer and stronger than the Engelmann spruce of group B, and thus was used more extensively in group C beams to yield predicted ultimate strength nearly equal to beams of group B.

Group D utilized visually graded hem-fir lumber. Johnson (10) demonstrated the potential for developing a high-strength combination using this type of lumber. (Data developed in the present study could increase confidence in the strength of beams built from visually graded hem-fir lumber.) A nine-lamination beam was designed using somewhat conservative assumptions for CWS values in bending. The L1 tension lamination was graded to have a specific gravity of at least 0.39—somewhat above average.

Table 1.--Summary of beam d[illegible]sign based on as[illegible] lumber properties

Group	Target near minimum MOR[1]	Stresses at target MOR[1] at locations shown in figure 3[2]							[illegible]OR	[4] z/d	Strength ratio[5]	Compression bonus required[6]	Design E[7]
		f_1	f_2	f_3	f_4	f_5	f_6	f_7					
	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}					Million lb/in.^{2}
A	4,350	5,070*	3,540	1,310	1,440	4,580	--	--	1.17	0.49	0.685	1.10	1.67
B	4,580	5,340*	4,060	2,770	920	1,510	3,060	4,900	1.17	.48	.722	1.18	1.65
C	4,600	5,320*	4,060	2,780	2,010	2,760	4,740	--	1.16	.49	.720	1.16	1.69
D	2,980	3,340*	2,210	1,390	1,470	2,960	--	--	1.12	.49	.647	1.23	1.43
E	5,410	6,020*	4,220	2,380	3,630	5,790	--	--	1.11	.49	.717	1.25	1.82
F	4,760	5,290*	3,670	2,160	3,270	5,010	--	--	1.11	.49	.720	1.23	1.67
G	5,340	5,960*	4,160	2,130	2,230	5,510	--	--	1.12	.49	.812	1.34	1.68
H	3,340	3,930	2,530*	1,190	1,300	3,430	--	--	1.18	.49	.624	1.45	1.42

1/ MOR = modulus of rupture; target moment resistance divided by gross section modulus.

2/ Critical stress and location denoted by *.

3/ Ratio of maximum outer fiber stress to target MOR.

4/ Fraction of the depth, measured from the tension side, to the neutral axis.

5/ Ratio of beam strength to that consisting of clear material of the type in the outer tension lamination.

6/ Tension stress assumed to control, but compression bonus shown needed to satisfy this condition.

7/ Design modulus of elasticity (E) is 95 pct of the Σ EI $\div$ I.

Beams of E-Rated Lumber

Four combinations were designed to use E-rated material of four different species groups for the outer laminations. Tension laminations of three different nominal E-grades were used. One requirement of all E-rated lumber was that it meet the visual requirements of the L3 laminating grade (or No. 2 for southern pine).

Group E used all Douglas-fir material with six of the nine laminations visually graded L3. The 2.2E outer tension laminations met the visual requirements for 2,700f-2.2E machine stress-rated (MSR) lumber *(24)* and was referred to as E2.2T. The second tension lamination met the 2,400f-2.0E MSR visual grade requirement (E2.0T). The outer compression lamination—a 2.0E grade—met visual requirements, not of the 2,400f MSR grade but of the L3 grade; it was referred to as E2.0C.

Group F used all southern pine material with six of the nine laminations of No. 2MG *(20)*. The 2.0E outer tension lamination met visual requirements for the 2,400f-2.0E MSR grade *(20)* and was referred to as E2.0T. The second tension lamination met the 2,100f-1.8E visual grade requirements (E1.8T). The outer compression laminate was a l.8E grade but had visual characteristics permitted in the No. 2 lumber (El.8C).

Group G closely resembled group F with hem-fir lumber except that two 1.8E compression laminations were used. Inner laminations were L3 hem-fir as used in group D.

Group H was to explore a potential species-independent system for manufacturing glulam beams. The one requirement was that all material should come from a grade and species having an average nominal E of at least 1.0 x 10^6 lb/in.^{2}. The outer tension lamination was about 1.8E, had the edge knot restriction of 2;100f-1.8 MSR grade *(24)*, and was referred to as E1.8T. The second tension lamination was about 1.5E and had the edge knot requirements of the 1,650f-1.5E grade (E1.5T). The outer two compression laminations were also 1.5E but had visual characteristics of the L3 grade (E1.5C). Inner laminations were L3. Lodgepole pine lumber comprised the outer two top and bottom laminations for group H. This material has been evaluated *(8)* and used to a limited extent *(2)* for laminating, is readily available in the E ranges selected, and is known to have knots representing near maximum size permitted in the grade. Engelmann spruce was used for the inner lamination because an L3 grade has an estimated average E of about the minimum required (1 million lb/in.^{2}).

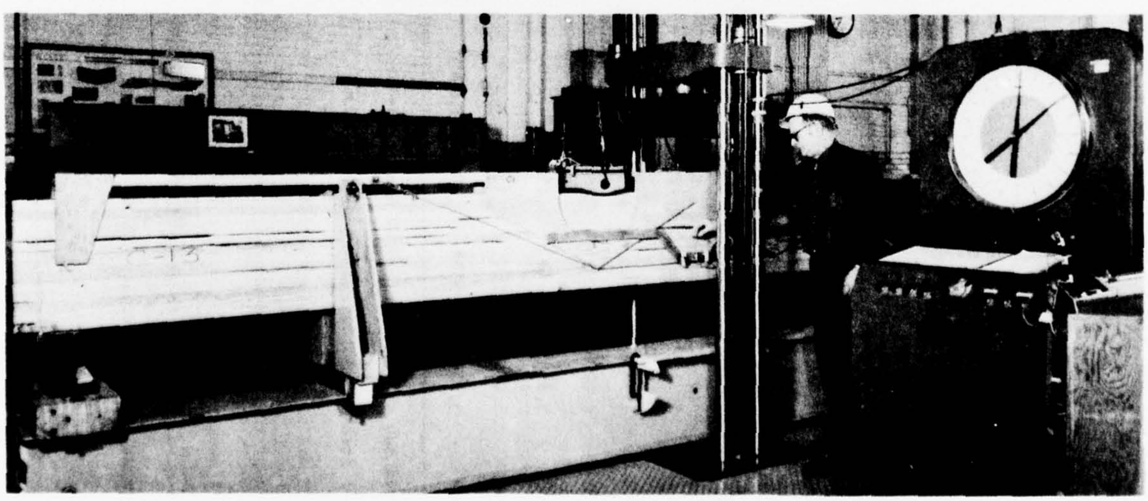


Figure 4.—A group C Douglas-fir beam 3-1/8 in. by 18 in. by 20 ft, showing full-span yoke deflectometer and lateral supports, also used for 12-in.-deep beams. Beam span was 19 ft with 4 ft between the loading heads. For these 18-in.-deep beams, additional lateral support bracing was added near the top of the shown supports to prevent lateral buckling. Note the wane apparent in the inner No. 3 Douglas-fir laminations.

(M 143 179)

Tension Lamination Criteria

Previous work has repeatedly indicated a need to assure visual quality for the outer tension lamination. Although visual criteria are not currently required for beams less than 16 in. deep, specific guidelines were used to select a visual tension lamination grade for the various combinations. The indicator of required visual quality was the strength ratio of the tension side of the beam as determined by the I_K/I_G concept.

The grades developed closely approximated AITC grades *(1)* except that the different effect of edge and centerline knots was recognized for all grades. Edge knots were defined as those with associated grain deviations closer than 1/2 in. from the edge. For grading the tension laminations, a 1-ft length was assumed to constitute a cross section. In addition, limitation on low density pieces was applied to the visually graded tension laminations. For the E-rated tension lamination, no large change in properties from one end to the other was allowed.

Material preparation

The L3 and No. 3 Douglas-fir and No. 2MG southern pine were finger jointed following grading and the lumber evaluated as 20.3-ft-long pieces. All other lumber was processed prior to finger jointing as follows:

1. Each piece of lumber was identified and approximate dimensions and moisture content measured. Weight and E were then determined using an E-computer.
2. The lumber was finger jointed into 20.3-ft-long laminations. For some of the beams, end joints occurred near midlength of the outer tension laminations.
3. Laminations were assigned to beams according to their grade and classification; PS 56-73 was followed for end-joint spacing.

Lumber used as midlength tension laminations was especially selected to have a strength-reducing characteristic near the maximum described in table 2. The requirements for pith-associated wood currently used *(1)*, which limit the amount to one-eighth of the cross section, were applied to the ends of all of the tension laminations. For the visually graded tension laminations of groups A-D, an attempt was made to obtain material of near average density. Douglas-fir pieces (groups A, B, and C) with a low specific gravity (below 0.45) or a high specific gravity (above 0.53) were excluded as not typical of near average material. A similar range for hem-fir (group D) was 0.39 to 0.42.

All group A tension laminations were from L1 material. For group B, four tension laminations (for B-01, -02, -03, and -05) were

Table 2.--Grading requirements used for tension laminations of the eight combinations

Group	Nominal grade	Grade description: Limitation based on knots and grain deviation — Edge	Grade description: Limitation based on knots and grain deviation — Centerline	Grade description: Maximum slope-of-grain	Approximate equivalent AITC visual grade (1)
		Pct	Pct		
A,D,H	65	43	50	1:12	301-20
B,C,E	70	36	42	1:16	301-22
F	75	30	35	1:16	301-24
G	80	24	28	1:16	301-26

from L2 dense with the remainder from L1. For group C, one tension lamination was L1 (C-04) and all others were L2D. All group D tension laminations were from L1 (dense) visually graded hem-fir.

Tension laminations for groups E and G were to be selected from material that was E-rated by the CLT-1 machine. However, shortages developed in both groups so that to obtain desired visual characteristics it was necessary to select material from visually graded lumber using E-computer stiffness values. Thus, two beams in group E (E-24 and E-27) and four beams in group G (G-01, -02, -03, and -05) had tension laminations not processed through the CLT-1 machine but with stiffness values determined by the E-computer.

The two group E tension laminations not CLT-1 graded were from L1 material. Based on E-computer data, these two had stiffness values near to the remaining 13. The four group G tension laminations were from visually graded L1 (dense) hem-fir. These four were intentionally selected with E values lower than the target average E of 2.0 million lb/in.^{2} so as to balance the distribution. The four with lower values brought the overall distribution and average close to the minimum target specification.

For groups F and H, tension laminations were selected by E-computer results. Frequency distributions similar to those obtained for lumber used in groups E and G were simulated with the E-computer.

Group F tension laminations were selected from No. 1 and No. 2 material that had been E-rated with an E-computer: Seven beams had No. 1D, another seven had No. 2D, and one had a No. 1MG visual grade. All group H tension laminations were first selected based on static E determined over full span with a weight and dial gage at the lumbermill. Final selection was by E-computer. The resulting E distribution approximated the desired one.

A special attempt was made to obtain at least one E-rated tension lamination each in groups E, F, G, and H which had an E slightly below 200,000 lb/in.^{2} less than the nominal E. Conversely, not more than one exceeding the nominal E by this amount was permitted. No tension laminations with E values by E-computer that differed from the average by more than 13 pct were used.

All lumber for the tension side met or exceeded the same minimum criteria as the outer midlength tension laminations but did not necessarily have near-maximum strength-reducing characteristics. All tension laminations were manufactured such that near-maximum allowable strength-reducing characteristics were placed within 2 ft of midlength. Also, 30 to 40 pct of the beams intentionally had finger joints in the highly stressed midlength region.

Beam Manufacture

Except for the differing lumber grades, manufacture followed PS 56-73 (22). Group F beams were manufactured by a commercial laminator who commonly processes southern pine material. All other beams were manufactured by a laminator who commonly processes Douglas-fir.

For group F material, a phenol-resorcinol adhesive was used with a finger joint whose profile was visible on the wide face. For all other material, a melamine-urea adhesive was used with a finger joint whose profile was visible on the narrow face. A common finger joint profile was used: 1.1-in. length, 1/4-in. pitch, 0.030-in. fingertip width.

A major problem developed when processing the No. 3 Engelmann spruce material. Considerable twist and bow in much of this lumber made it incompatible with the automatic finger-jointing equipment. Thus many of the finger joints were not properly alined during mating. Also, end pressure had to be nearly eliminated during curing to prevent buckling of the laminations. As a result, quality of many of the resulting finger joints in the No. 3 Engelmann spruce was questionable upon visual inspection. However, considering the axial and bending stresses to which finger joints would be subjected in the inner laminations of group A and B beams, the relative quality of the material, and the time and machine modifications necessary to correct the problem, it was decided to use the material as initially manufactured. Except for adjustments of end pressure for the other species of wood, the remaining material was processed with few problems.

Following finger jointing, all beams were assembled from the various grades, and the location of each piece of lumber was noted. At this time, the No. 3 and L3 Douglas-fir and the No. 2MG southern pine laminations were E-rated, weighed, and their moisture content

determined. Knots were also measured in the midlength 10 ft of all laminations.

Before gluing, all laminations were surfaced to a thickness of about 1-3/8 in. The beams were then immediately glued using a phenol-resorcinol adhesive. After removal from clamps, they were surfaced to a 3-1/8-in. width and trimmed to a 20-ft length. They were then shipped to Madison, Wis., and stored indoors for 1 to 2 mo prior to testing.

RESEARCH METHODS

Equipment

Test equipment and procedures conformed to ASTM D 198 (5). All beams were loaded on a 19-ft span with 4 ft between loading heads (fig. 4). Lateral supports at about 4 ft from each end had roller contacts to minimize frictional force. Supports shown in figure 4 were used for the 12-in.-deep beams while additional bracing was added near the top of the 18-in.-deep beams.

To obtain a complete record of the full beam deflection, a yoke deflectometer was developed. Using an electrical transducer, deflection measurements over the 19-ft full span were continuously recorded to failure with no threat of damage to the equipment. Deflection measurements were also made over the 4-ft short span between load points using a different yoke arrangement (fig. 4). An electrical transducer was also used to measure this short span deflection.

A two-channel scanning X-Y recorder was used to record test machine load along with the two deflection measurements.

Procedure

After each beam was properly alined in the test equipment, a preload of about 200-lb/in.^{2} maximum stress was applied to assure proper contact. The X-Y plotting equipment was properly adjusted and loading was continuous to failure. Machine head speeds of about 0.8 in./min were used for the 12-in.-deep beams and 0.5 in./min for the 18-in.-deep beams. At about 40 to 50 pct of anticipated minimum strength, the equipment used to record deflection on the 4-ft span was removed to prevent possible damage at failure.

Many failures were expected to be sudden and complete. However, because some compression-type failures were also expected, test machine head movement continued until the machine load dropped below about 50 pct maximum.

Data Obtained

Dimensions of each beam were determined by measuring the cross-section at each load point and the total length. Each beam was also weighed before test and a photograph taken of the center 6-8 ft of the beam bottom. A continuous record of machine load versus both full-span and short-span deflections was obtained.

During test, audible cracking and visible splitting were recorded. Details of failure were noted and probable initiation points estimated. Moisture content was measured for each lamination near failure with a resistance type meter having 1-1/2-in.-long probes. Each beam was then photographed; if failure appeared to begin in a specific region, this was cut from the beam for further inspection.

PRESENTATION OF RESULTS

Lumber Properties

Lumber properties are found in appendix II along with detailed information on individual tension laminations for each group. Average properties of tension laminations are summarized in table 3.

Beams

Average properties of each beam group as determined by test are in table 4. Distribution of MOR and E data are shown in figures 5 and 6. Individual test results are in appendix III.

Table 3.--Summary of average properties of midlength tension laminations[1/]

Group	Nominal grade	Specific gravity[2/]	Moisture content[3/]	E[4/]	Average size of strength reducing characteristics	
					Knots	Knots and grain deviation
			Pct	Million lb/in.^{2}	Pct	Pct
A	65	0.50	12	2.21	23	40
B	70	.52	12	2.41	17	35
C	70	.50	11	1.94	24	37
D	65	.39	11	1.63	26	41
E	70	.49	11	2.17	23	40
F	75	.52	15	2.00	13	31
G	80	.42	10	1.99	17	28
H	65	.44	10	1.78	24	38

1/ Averages are for the 15 pieces of lumber used.

2/ Based on weight adjusted to ovendry and volume at time of test.

3/ Determined with power-loss type moisture meter.

4/ Modulus of elasticity (E) determined with E-computer.

Test Beam Failures

Failures were expected in several different categories: Shear; compression; and tension involving finger joints, knots, or slope-of-grain. Shear failures were expected in several group B and C beams; however, only one (B-10) failed in that manner. One beam in group A also failed in shear (A-05).

Compression failures were expected in each group but occurred to a significant extent only in groups D, G, and H. Three beams each in groups G and H and four beams in group D developed compression wrinkles located away from the loading heads which were severe enough to significantly modify the stress distributions. Subsequent loading resulted in a tension mode of failure in all beams but one. For this beam, G-13, the load had decreased to less than 75 pct ultimate when the limit of machine head travel was reached. Although no tension failure occurred, compression wrinkles were apparent at several locations throughout the upper half of the beam (fig. 7).

Most beam failures appeared to begin in

Table 4.--Summary of average beam properties[1/]

Group	Dimensions[2/]		Moisture content[3/]	Specific gravity[4/]	Modulus of rupture		Modulus of elasticity		Shear stress at failure	Strength weight factor[6/]
	Width	Depth			Average	Coefficient of variation[5/]	Full span	Short span		
	In.	In.	Pct		Lb/in.^{2}	Pct	Million lb/in.^{2}	Million lb/in.^{2}	Lb/in.^{2}	
A	3.08	12.39	9	0.46	5,040	24	1.80	1.94	173	1.09
B	3.08	17.89	10	.47	5,560	14	1.78	1.87	276	1.18
C	3.08	17.89	9	.49	5,880	17	1.81	1.82	292	1.20
D	3.07	12.39	9	.37	5,110	12	1.31	1.37	176	1.38
E	3.08	12.39	11	.52	6,170	16	2.05	2.19	212	1.19
F	3.14	12.35	11	.50	6,590	17	1.69	1.92	226	1.32
G	3.08	12.38	9	.40	6,210	15	1.70	1.84	214	1.55
H	3.08	12.37	10	.42	5,220	19	1.42	1.56	179	1.24

1/ Averages are for 15 tests.

2/ Average of measurements made at load points.

3/ Determined following test using resistance-type meter with 1-1/2-in. needles. Recommended species corrections were applied.

4/ Based on weight and volume at time of test (weight adjusted to ovendry).

5/ Standard deviation ÷ average.

6/ Average modulus of rupture ÷ (specific gravity x 10,000).

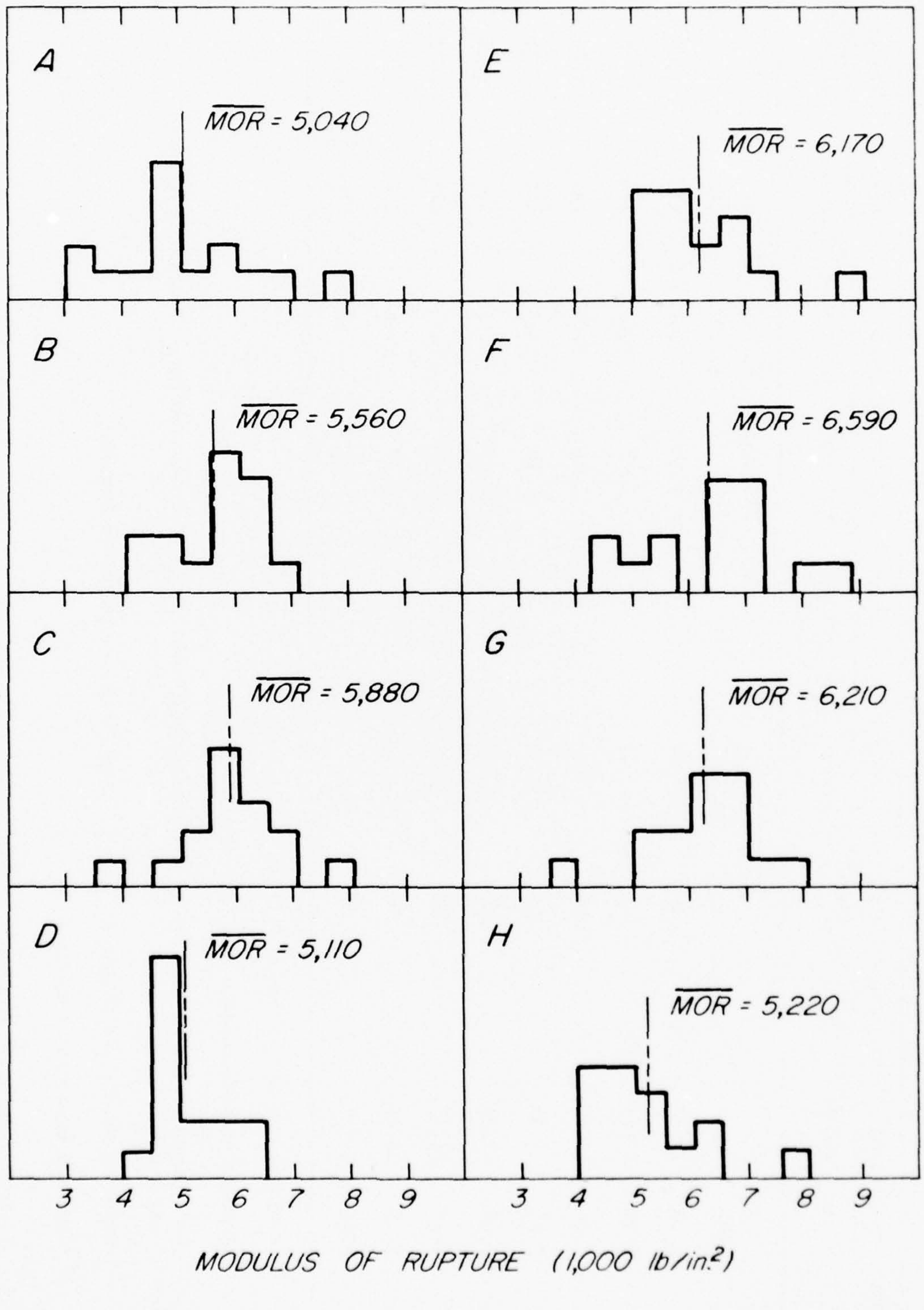


Figure 5.—Distribution of beam modulus-of-rupture values, also showing average values ($\overline{MOR}$).
(M 145 169)

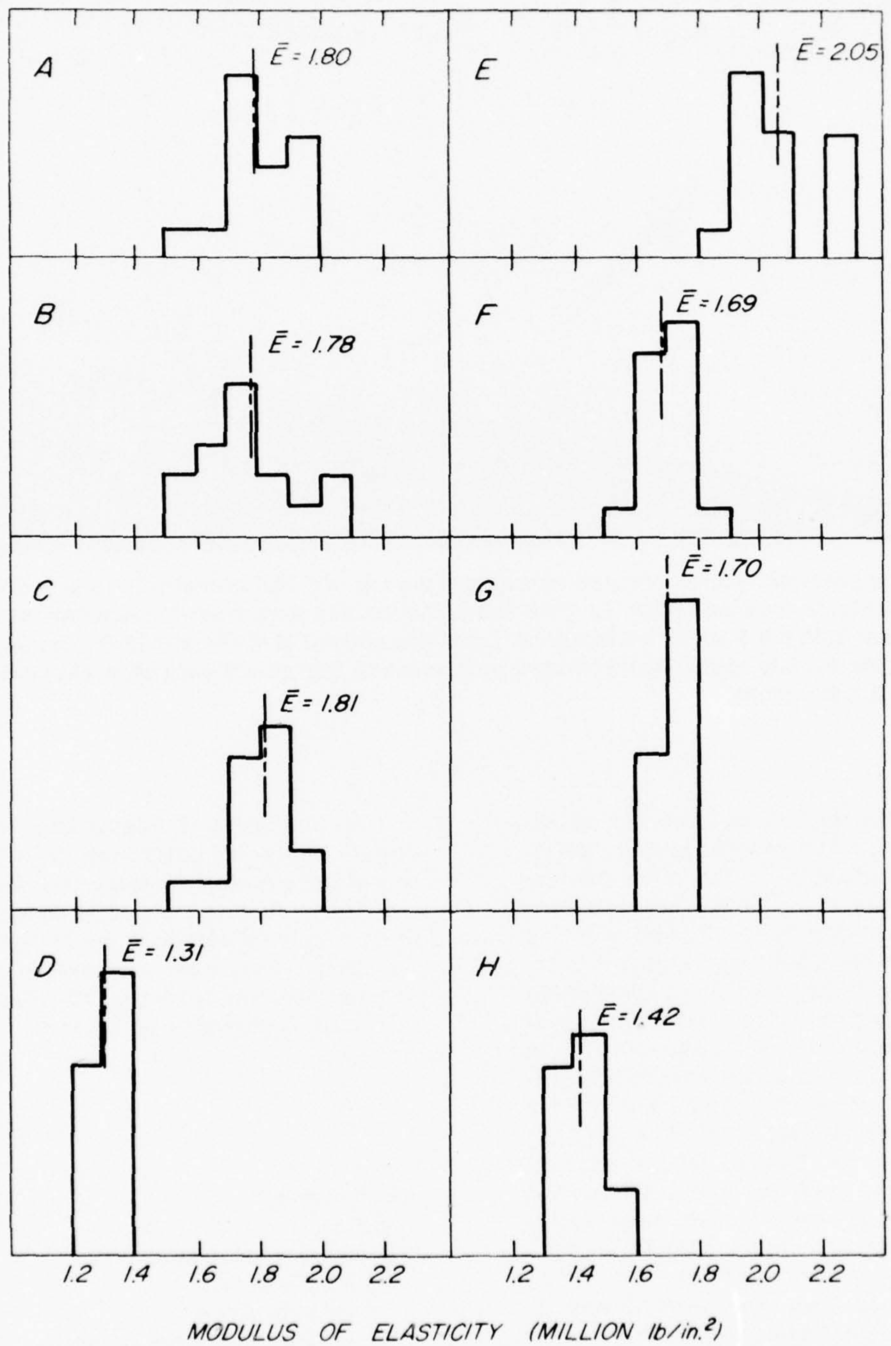


Figure 6—.Distribution of modulus-of-elasticity values for full-span beams, also showing average values ($\overline{E}$).
(M 145 170)

Figure 7.—Compression failures occured throughout the top one-half of beam G-13 at two locations within the highly stressed region. Large knots in the top and third-from-top laminations were involved near both the 9- and 11-ft locations. *Load was applied at the 8- and 12-ft locations.* A total of 10 beams developed significant compression wrinkles; the other 9 were generally limited to the top 2 or 3 laminations.
(M 143 194)

the outer tension lamination. Many beams failed through knots and associated grain deviation in the midlength of the outer tension lamination. Forty-seven of the beam failures were attributed directly to strength-reducing characteristics identified prior to test (fig. 8).

Thirty-four beams had finger joints within the most highly stressed (midlength) region of the tension lamination while another 48 had joints where the stress was at least 75 pct maximum. An additional 26 had joints where the stress level was between about 50 and 75 pct maximum. For 26 beams, failure was attributed solely to the finger joint in the tension lamination. Most were in the most highly stressed 4 ft (the midlength); all but two of the others were in the zone with at least 75 pct maximum stress. Two beams—A-09 and B-14—failed through finger joints in the tension lamination where the stress was only about 50 pct maximum.

An additional 17 beams failed such that finger joints in combination with other characteristics were involved (fig. 9).

The remaining 18 beams failed through knots or grain deviation in the tension lamination which appeared less severe than the selected characteristics (fig. 10). Beam failure types are summarized as follows:

Type	Number of beams	Pct
Shear	2	2
Compression	10	8
Tension		
Selected tension lamination characteristics	47	39
Finger joint alone	26	22
Finger joint and other defects	17	14
Other tension lamination characteristics	18	15

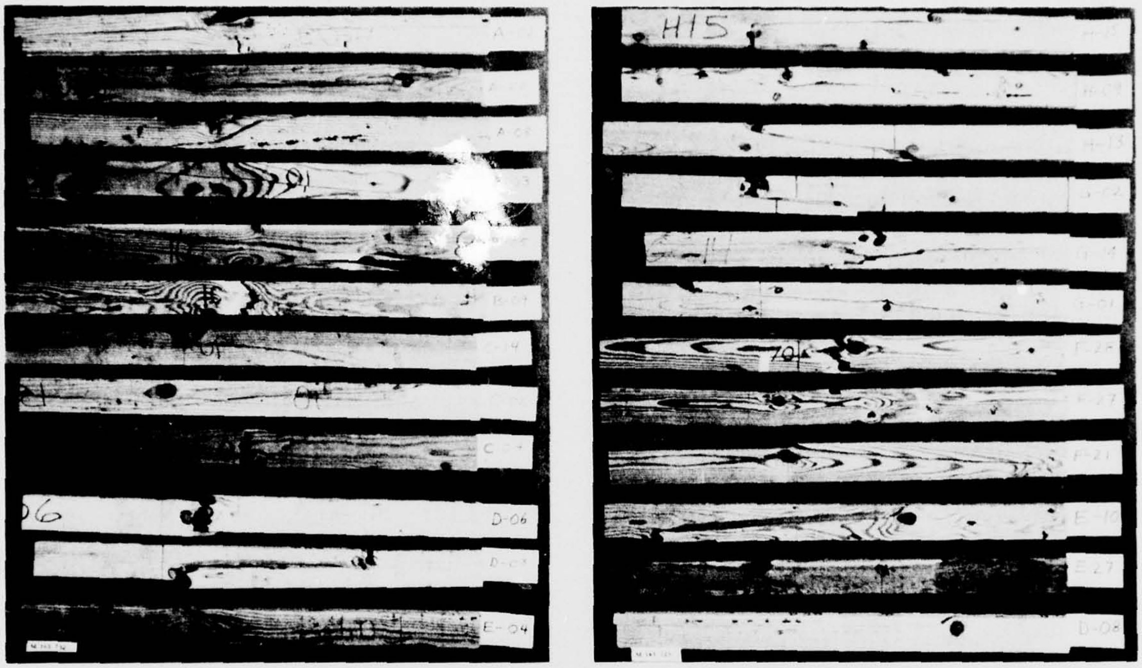


Figure 8.—Some of the midlength tension laminations from beams which failed through the selected visual characteristics; 47 of the 120 beams failed in this manner. (M 143 729, M 143 732)

Figure 9.—Some tension laminations from beams which failed through portions of a finger joint and also through either slope of grain or grain deviations nearby; 17 beams failed in this manner.
(M 143 731)

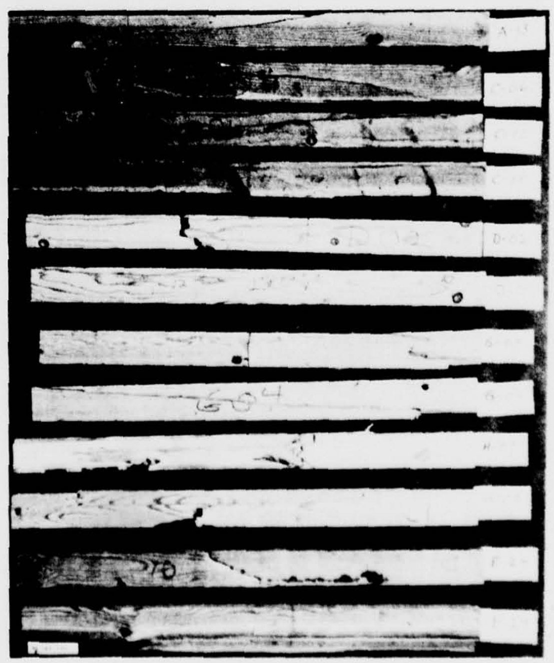


Figure 10.—Some midlength tension laminations from beams which failed through slope of grain or grain deviations and not at the selected characteristics; 18 beams failed in this manner.
(M 143 730)

ANALYSIS OF RESULTS

Modulus of Elasticity (E)

Table 5 compares average full span E of each beam group with the design E. Design E was assumed to be 95 pct of predicted E based on a transformed section analysis. For groups A, B, and C—those with visually graded Douglas-fir outer laminations—test values exceeded the nominal design goals by 7 or 8 pct. This reflects the 10-15 pct above-average stiffness of the L1 and L2 visually graded Douglas-fir available for the study. For the visually graded hem-fir beams (group D), the average test E was 8 pct below the design goal. This difference can be explained by the lower than anticipated stiffness of the L1 and L2 hem-fir lumber.

Three E-rated combinations (groups F, G, and H) had average test E essentially equal to the design goal. This was expected because the outer laminations which contribute most to beam stiffness were selected on the basis of their modulus of elasticity. For group E, the average test value exceeded the design goal by 13 pct. This difference was larger than expected and no explanation could be found for it.

Actual E values for all beams are compared in figure 11 to values predicted using known properties. Predicted E for the 120 beams ranged between 1.25 and 2.31 million lb/in.^{2} while test values ranged from 1.20 to 2.26 million lb/in.^{2}. A regression analysis suggested a line of best fit as

Table 5.--Comparison of design and actual modulus of elasticity (E) values

Group	Design E	Actual test E[1/]		Actual E ÷ design E
		Average	Coefficient of variation	
	Million lb/in.^{2}	Million lb/in.^{2}	Pct	
A	1.67	1.80	6.5	1.08
B	1.65	1.78	9.1	1.08
C	1.69	1.81	5.2	1.07
D	1.43	1.31	4.8	.92
E	1.82	2.05	6.0	1.13
F	1.67	1.69	4.0	1.01
G	1.68	1.70	2.4	1.01
H	1.42	1.42	4.2	1.00

1/ Based on 15 replicates in each group.

$$Y = 0.80X + 0.24 \quad (12)$$

where $\underline{Y}$ is actual full span E from test (million lb/in.^{2}) and

$\underline{X}$ is predicted E (million lb/in.^{2})

with a coefficient of determination (R^2) of 0.96.

The resulting intercept limits the usefulness of the equation. Overall, actual full-span E averaged 93.3 pct of the predicted values, suggesting an equation of the form

$$Y = 0.933X \quad (13)$$

where factors are as described for (12). This compares favorably with previous results *(15)* and confirms the use of the 0.95 factor proposed.

As expected, short-span E values were generally somewhat larger than full-span values—averaging 7 pct higher. This difference is consistent with differences previously found *(15)*. The short-span E value also had larger variability; the coefficient of variation averaged about twice that of the full-span E.

Modulus of Rupture

Predictability of the MOR can be measured by comparing the target strength with actual ultimate strengths (table 6). At least one beam in five of the eight groups was below the near-minimum predicted (target) strength. In groups A and E, 4 of the 15 beams were below the target values.

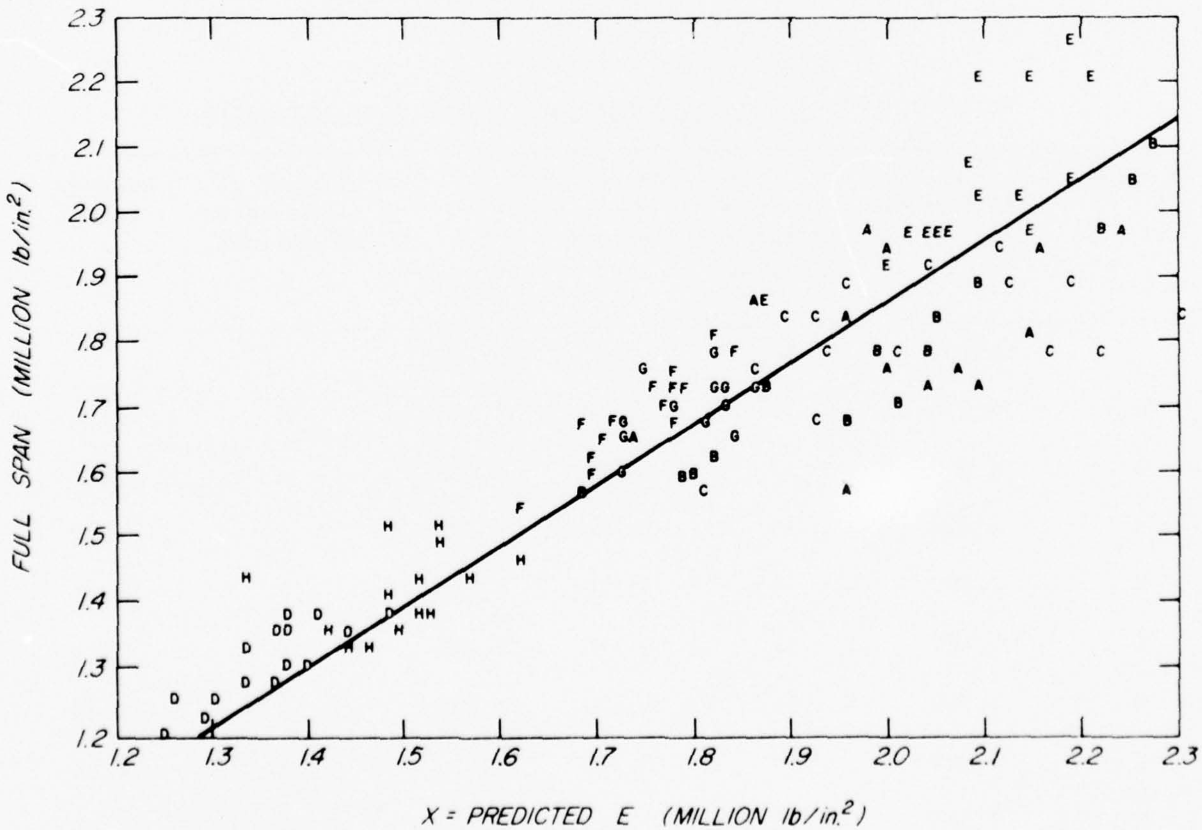


Figure 11.—Comparison of actual and predicted full-span modulus of elasticity. Letters denote beam group for each specimen.

(M 145 166)

Group A

The low strength beam (A-12) attained only 73 pct of the near-minimum predicted value. The failure of this beam, along with another (A-14) which attained 88 pct of the desired value, seems to have been caused by a finger joint in the tension lamination. Examination of these two finger joints indicated low percentage of wood failure. Improved bonding, especially in the latewood, would undoubtedly have improved the strength of these two beams along with beams A-07, A-09, and A-10.

One beam failed in shear at 79 pct of the design goal due to shake in an inner Engelmann spruce 2 by 4 not detected during grading. Before the beam test, the shake was apparent over the end 8-9 ft. Laminating grades of lumber do not permit this type of defect and the No. 3 grade for use in glulam should prohibit it also.

The fourth beam below desired values appeared to fail due to combined effects of slope-of-grain and a finger joint at 98 pct of the desired value.

Reanalysis of the combination using actual knot data for the lumber (appendix II) revealed that the predicted near-minimum MOR would be 2 pct lower at 4,270 lb/in.^{2} (table 7), a value affected by the nominal "65" grade tension lamination which was assumed to limit the outer fiber strength ratio to 0.674. The 4,270 lb/in.^{2} value is essentially equal to the fourth lowest strength, leaving three beams significantly below it.

These three beams failed such that, had the strength reducing characteristic in the tension lamination been smaller, there is no reason to believe they would have been stronger. Three other beams failed between the 4,270 lb/in.^{2} value as limited by the tension lamination quality and the 4,660 lb/in.^{2} value

Table 6.--Comparison of target and actual beam strengths

Group[1/]	Target near minimum MOR	Strength data			Number of beams below target MOR	Average ÷ target
		Moisture content	Average MOR	Low strength beam		
	Lb/in.^{2}	Pct	Lb/in.^{2}	Lb/in.^{2}		
A	4,350	9	5,040	3,190	4	1.16
B	4,580	10	5,560	4,030	2	1.21
C	4,600	9	5,880	3,500	1	1.28
D	2,980	9	5,110	4,230	0	1.71
E	5,420	11	6,170	5,120	4	1.14
F	4,760	11	6,590	4,780	0	1.38
G	5,340	9	6,210	3,810	1	1.16
H	3,340	10	5,220	4,240	0	1.56

1/ Fifteen beams in each group.

as limited by the I_K/I_G analysis; tension lamination defects appeared to be the primary cause. These observations strongly indicate that the strength as limited by the tension lamination quality is close to that assumed.

Group B

Two beams failed below the desired strength, one (B-12) at 88 pct and another (B-04) at 97 pct of the desired value. Beam B-12 failed near a finger joint but only about 5 pct of the actual joint was involved. The remainder of the cross-section failed in an unusual manner (fig. 9). Although low wood failure was apparent over the small portion of the finger joint, the primary weakness seemed to be in wood quality near the joint. Beam B-04 failed through a maximum sized tension lamination characteristic.

The reanalysis (table 7) shows that a design MOR about 5 pct higher may have been attained with a better quality tension lamination. However, the nominal, "70" grade tension lamination limits the overall strength ratio to 0.724, essentially the same ratio as derived from the preliminary design. Thus, no change was found upon reanalysis. Note that the one beam failing at 97 pct of the desired value and another just 2 pct over the desired value both failed at near-maximum sized tension lamination defects. This also indicates that the beam strength as controlled by the tension lamination is as assumed.

Group C

One beam, C-14, failed at 76 pct of the desired MOR of 4,600 lb/in.^{2} apparently due to a maximum defect in the tension lamination. Reevaluation of this lamination revealed slope-of-grain within the failure region steeper than estimated (fig. 8). Another beam failed at exactly the design value due to a maximum ten-

Table 7.--Results of reanalysis using actual knot data

Group 1/	Strength ratio by I_K/I_G	Compression bonus required	Strength ratio limited by tension lamination quality	2/ $\frac{Td}{2Z}$	Target near minimum MOR by reanalysis	Comparison with target MOR from table 1
					Lb/in.^{2}	Pct
A	0.734	1.41	0.674	0.858	4,270	98
B	.761	1.43	.724	.857	4,590	100
C	.756	1.30	.724	.865	4,630	101
D	.589	1.20	.674	.894	2,710	91
E	.686	1.48	.724	.898	5,190	95
F	.752	1.44	.774	.900	4,980	104
G	.771	1.64	.824	.895	5,080	95
H	.640	1.49	.674	.848	3,420	102

1/ Fifteen beams in each group.

2/ Factor for use in equation (10).

sion lamination defect. The strength of all other beams greatly exceeded the desired value.

A reanalysis with actual data would result in an increased predicted MOR. However, the nominal "70" grade tension lamination limited the design MOR to within 1 pct of the preliminary assumption. Thus, the reanalysis results in no change.

Overview of Groups A, B, and C

Overall, these three groups had 7 of 45 beams which failed to meet desired levels. Two of these 7 beams had strengths within 2 or 3 pct of the desired value but the other 5 were more than 10 pct below the desired value.

Two of these five lower strength beams failed through finger joints in the outer tension lamination; improved finger joint quality would undoubtedly have increased their strength. A third beam failed due to shake in an inner lamination. The other two beams failed due to *characteristics in the tension laminations.* With one, the extent of grain deviation associated with a knot was considerably greater than had been assumed during selection. For the other, wood quality near the finger joint appeared to limit strength but with no visual indication of the reason. These last two beams suggest limitations to visual grading in assessing lumber strength.

Average MOR values for groups A, B, and C exceeded the near-minimum predicted MOR by between 16 and 28 pct (table 6). For more favorable results, this should have been at least 30 and more likely 40 pct. Test results indicate that (a) several of the minimum values are lower than desired, and (b) overall average strength values are low. In the analysis it was assumed that the outer tension laminations were L1 material. Actually, a significant number of the near-minimum quality tension laminates were from material graded L2D by the plant (2 for A, 4 for B, and 14 for C). This was obviously some of the better L2D material; knot analysis indicated it to be typical of the L1, and not the L2.

Group D

All beams greatly exceeded the near-minimum design MOR of 2,980 lb/in.^{2}. In fact, the lowest strength beam exceeded this value by 42 pct. Reanalysis resulted in yet a lower strength with a predicted minimum MOR of only 91 pct of the 2,980 lb/in.^{2} value. The uniformly high strength values suggest that the CWS value used in preliminary design was too conservative. These results are consistent with Johnson's in that CWS values considerably higher than obtained from ASTM procedures appear applicable.

Group E

Beams E-04, E-24, and E-27 all failed below the desired level (fig. 8) through maximum defects in the tension lamination. One other (E-05) failed through a finger joint with a high percentage of wood failure. These four all ranged from 94 to 98 pct of the 5,420 lb/in.^{2} target value.

Reanalysis resulted in a 4 pct lowering of the predicted near-minimum MOR. Two beams remained below this value. Both failed at tension lamination maximum defects but were within about 1 pct of the adjusted target value (5,190 lb/in.^{2}).

Group F

No beams of this group were below the desired MOR but two had strength only about 1 pct above this 4,760-lb/in.^{2} target value. One of these failed through a finger joint and one through a tension lamination defect.

By reanalysis, predicted minimum strength increased about 5 pct to 4,980 lb/in.^{2}. The two beams previously just over the desired value then fell to 96 pct of that value.

Group G.

The one beam below the desired value was significantly so at 71 pct of the 5,300-lb/in.^{2} target value. This beam, G-01, failed through a maximum tension lamination defect and along slope-of-grain (fig. 8). It is uncertain why this beam had low strength. However, the midlength tension lamination was one of only four pieces not processed through the CLT-1 machine. The source of these four pieces was also different in that they were grand fir material from Idaho.

Reanalysis resulted in a 5 pct decrease in design MOR for group G but essentially did not change the analysis. The low beam averaged 75 pct of the 5,080-lb/in.^{2} desired value.

Group H

All beams exceeded the near-minimum desired value of 3,340 lb/in.^{2}. The low strength beam greatly exceeded this (by 27 pct), indicating that conservative assumptions were

used in design. Reanalysis increased the near-minimum MOR by only 2 pct.

Overall Comments

Except for group D, reanalysis using actual knot data had little effect (5 pct or less) on the predicted near-minimum MOR. For group D, the reanalysis decreased the predicted value by 9 pct. Thus, in general, knot data used in the preliminary design were fairly representative of the actual lumber used.

In only two groups, D and H, did the average MOR exceed the near minimum predicted by over 40 pct (table 6). For these two groups, high MOR values suggest that the CWS values used in the analysis are too conservative. In group F, for which the average MOR exceeded the estimated near minimum by 38 pct, the assumed CWS value may be near the desired value. For the other groups, which had Douglas-fir and E-rated hem-fir outer lamination, the CWS value should be reexamined.

Effect of Procedure for Selecting Tension Laminations

The original visual lumber grade of the tension lamination had no obvious effect on the strength of beams in groups B, C, and F, where visual grading was used exclusively. For groups E and G, those beams where non-CLT tension laminations were used because of material shortage were among the lower strength ones. Four minimum strength beams in group E had MOR values between 5,100 and 5,300 lb/in.^{2}, and the only two beams with non-CLT graded tension laminations were within this range.

The three lowest strength beams in group G were represented by non-CLT graded tension laminations; the other beam with non-CLT material was above average. Similar comparisons within groups F and H are not possible because no tension laminations were CLT graded—all were selected either by E-computer (group F) or by dual criteria of static load and E-computer (group H).

This apparent difference in lumber quality with method of E-rating warrants closer examination. It is partially explained for group G because the E values (vibration) of the four non-CLT graded tension laminations were considerably lower than the others—intentionally so to simulate a 2.0E grade.

However, the same explanation cannot be applied to group E because tension laminations selected by E-computer had near average modulus of elasticity values. Also, in groups F and H the modulus of elasticity of the tension lamination did not seem related to beam strength.

Differences between the E-computer and the CLT-1 machine might be examined to explain low strength beams in groups E and G. However, all group F and H tension laminations were selected by the E-computer and all met or exceeded the desired strength values.

Finger Joint Quality

Several beams failed through finger joints in the tension lamination with a low percentage of wood failure. Some finger joints, however, exhibited high percentages of wood failure and probably developed the full potential strength of the finger joint design. Many of the finger joint failures showed excellent bonding in the earlywood with poor bonding in the latewood, a condition not restricted to any species or growth rate. The joint strength, and consequently the beam strength, appeared to be limited by the amount and strength of earlywood present.

If higher strength joints in tension laminations are desired, improved joint design, better adhesive systems, and improved quality control techniques all appear to offer potential.

Comparison of Strength-Weight Factors

The several different species and two grading methods used provided an opportunity to determine the relative strength-weight efficiencies of the different beam groups. This factor has little to do with design and probably relates most closely to ease of handling and shipping.

The ratio of the average MOR to specific gravity was divided by 10^5 to yield factors near 1 for the eight groups (last column, table 4). Higher factors denote "more strength per lb of material."

All factors for the Douglas-fir groups (A, B, C, and E) were between 1.09 and 1.20, a range lower than for the other four groups. Group G, made using E-rated hem-fir, had the highest factor: 1.55. Group D, which also contained hem-fir, but all visually graded, had a

somewhat lower factor of 1.38. The southern pine (group F) and white wood (group H) fell between the hem-fir and Douglas-fir; values were 1.32 for group F and 1.24 for group H.

Although many other factors influence material selection, these data indicate that hem-fir lumber provides the greatest return in average bending strength per lb of material used in manufacture.

Influence of Wane

Groups B and C were designed to have a higher probability of horizontal shear failure than the other groups. However, only one of these 30 beams was believed to have failed in shear, i.e, beam B-10 at a calculated shear stress of 280 lb/in.^{2}. This was near the average calculated shear stress for the other 29 beams which failed in bending.

Design goals (about 1/2 target near-minimum value) for group B were 90 and for group C 110 lb/in.^{2} in horizontal shear. These represent two-thirds of the nominal design values for lumber without wane or splits. All 30 beams can be analyzed by dividing the calculated horizontal shear stress at failure by the design goals and examining the ratios. Individual ratios varied from 1.58 to 3.70 with an average of 2.86. An estimated fifth percentile would be about 2.1.

It is extremely difficult to arrive at any conclusions on shear strength of the beams with wany lumber in the interior laminations because 29 of the 30 failed such that this lumber did not appear to influence failure. What is significant is that no large shear weaknesses were apparent due to the wany lumber. Thus, the one-third reduction in design strength due to wane amounting to one-sixth of the width on either or both edges appears to be adequate.

Compression Bonus

One purpose of this study was to determine whether the grade of lumber on the compression side of glulam beams could be significantly reduced without developing compression failure. The amount by which nominal design stress on the tension side exceeded that on the compression side was denoted by the ratio of these two stress values and called a "compression bonus."

No compression failures were apparent in any of the Douglas-fir or southern pine groups. Discounting slight wrinkles in the top lamination at the loading head, only three groups had beams which developed obvious compression failures: Three beams each in groups G and H and four beams in group D developed compression wrinkles to the extent as to likely change the stress distribution in the cross section.

The required compression bonus in the different groups to maintain a tension mode of failure is shown in table 8. Based on assumed properties, a compression bonus of at least 1.2 (group D) was required to induce a small incidence; a factor of 1.5 (group H) did not create any predominance of compression failure. Using actual knot data for the beam analysis, compression bonus factors of 1.3-1.48 did not induce any failure in the Douglas-fir or southern pine. The test definitely indicates that a compression bonus of some value above unity is justified.

Although the results do not suggest any specific value of compression bonus for design of glulam beams, a factor of at least 1.3 appears to be justified. If 1.3 were used with the design concept proposed, low incidence of compression failure would probably result in any beams tested. A 1.4 or 1.5 factor may introduce more compression failures and lower average strength but yet is not likely to result in any beam strengths low enough to affect design levels.

Analysis of CWS Values

Many CWS values in bending for the different grades and species were assumed in order to design the various groups. The CWS values used were estimated near-minimum ultimate bending stresses for 12-in.-deep clear wood glulam beams consisting entirely of the described material (appendix I).

Results of this study along with results of many other recent large glulam beam tests provided an opportunity to analyze these estimated values. Details of the analysis are given in appendix IV and only the general trends summarized in table 9 will be discussed here.

For dense, visually graded Douglas-fir, the data indicate that when all grading and manufacturing variables in the research beams are considered, the CWS value at the 5th percentile should be less than the 7,390-lb/in.^{2} value assumed. At 75 and 90 pct levels of confidence, values are 6,460 and 6,310

Table 8.--Compression bonus factor

Group[1/]	Compression bonus factor required for balanced design: Assumed knot data	Compression bonus factor required for balanced design: Actual knot data	Compression-side failures: Number	Compression-side failures: Frequency
				Pct
A	1.10	1.41	--	0
B	1.18	1.43	--	0
C	1.16	1.30	--	0
D	1.23	1.20	4	27
E	1.25	1.48	--	0
F	1.23	1.44	--	0
G	1.34	1.64	3	20
H	1.53	1.49	3	20
TOTAL			10	8

1/ Fifteen beams in each group.

lb/in.^{2}. Dense hem-fir resulted in quite similar values. This type of analysis does not account for the selection of near-minimum quality tension lamination in the test samples. Thus, the true value of the lower percentile for a representative population is probably less than the 5th; further analysis is necessary to determine its absolute value.

For E-rated material, the data do not show justification for any difference in CWS values for the 2.0E through the 2.6E grade. CWS values of 7,000 and 6,800 lb/in.^{2} for 75 and 90 pct levels of confidence could probably be justified for this range of E-grade. These are somewhat higher than for dense visually graded Douglas-fir.

Both the 1.6E and 1.8E grades have somewhat lower CWS values. Values of 5,600 and 5,200 lb/in^2 are suggested for the 1.8E grade for the two levels of confidence but data are insufficient to develop a recommendation for the 1.6E grade. Some of the beams with E-rated laminations also included near-minimum quality tension laminations. As with the visually graded material, the exact effect of this technique on the statistical analysis is yet to be determined.

Table 9.--Results of clear wood bending stress analysis

Description of material[1/]	Number of beams	Clear wood bending stress			
		Mean	Standard deviation	Estimated fifth percentile (tolerance limit)	
				75% confidence	90% confidence
		$Lb/in.^2$	$Lb/in.^2$	$Lb/in.^2$	$Lb/in.^2$
		VISUALLY GRADED MATERIAL			
Dense Douglas-fir	88	8,760	1,300	6,460	6,310
Dense southern pine	28	10,790	1,860	7,280	6,870
Dense hem-fir	30	8,980	1,290	6,570	6,300
		E-RATED MATERIAL			
2.6 + 2.4	21	10,520	1,720	7,220	6,760
2.2	31	10,030	1,760	6,760	6,400
2.0	95	9,880	1,630	7,010	6,840
1.8	35	9,540	2,120	5,620	5,220
1.6	6	7,850	890	5,780	5,110

1/ Many of the beams were intended to be near minimum quality in that near minimum quality critical tension laminations were especially selected.

CONCLUSIONS

In considering the absolute values of beam strengths from this study, bear in mind that samples were selected to represent the near minimum quality for each grade. This was done by selecting near minimum quality outer tension laminations for the most highly stressed region.

Specific conclusions are:

(a) Design of unbalanced glulam beams using a "compression bonus" of 1.3 appears justified. The resulting reduced grade on the compression side will probably result in only a slight increase in the number of test beam failures in compression. A higher factor of 1.4 or 1.5 will introduce more compression failure in test beams; although a higher factor could lower the average bending strength, it would probably not affect the near-minimum strength.

(b) The procedure used to design visually graded glulam beams can be extended to beams with E-rated outer laminations. Clear wood stress values associated with 2.0E material are somewhat higher than for dense visually graded Douglas-fir. Data presented provide information on which to base the design of beams using E-rated outer laminations.

(c) Shear weaknesses larger than assumed were not apparent in beams made with lumber having wane occupying up to one-sixth of the width at either edge. Under dry conditions, design of such beams to a level of shear stress equal to two-thirds of that with wane-free lumber would appear justified. However, such lumber must be graded following the rules regarding splits and shakes.

Generally, results confirm previous findings in that the performance of some lower strength beams appeared to be limited by finger joint quality. Other beams below the target strengths indicated the importance of carefully grading tension laminations for the amount of grain deviation and the lower grade inner laminations for shake, which is not now permitted in laminating grades. Examination of tension laminations following failure suggested that, when questions existed regarding the amount of grain deviation, it was usually greater than assumed.

APPENDIX I

Appendix I.--Assumed lumber properties for designing glulam combinations

Species group and grading method	Grade	E[1/]	Knot data[2/] $\bar{X}$	h	Clear wood bending stress
		Million lb/in.^{2}	Pct	Pct	Lb/in.^{2}
Douglas-fir					
Visually graded[3/]	L1	2.1	6.9	32.4	7,390
	L2D	1.9	10.3	38.1	7,390
	L2	1.8	10.3	38.1	6,350
	L3	1.6	11.6	46.4	6,350
	No. 3	1.5	15	50	5,040
E-rated[4/]	E2.2T	2.2	5.2	32.6	8,400
	E2.0T	2.0	8.1	37.4	7,350
	E2.0C	2.0	10	36.9	7,350
Southern pine					
Visually graded[5/]	No. 2MG	1.5	7.6	43.3	6,350
E-rated[4/]	E2.0T	2.0	3.6	32.9	7,350
	E1.8T	1.8	7.6	43.3	7,350
	E1.8C	1.8	7.6	43.3	6,300
Hem-fir					
Visually graded[6/]	LLD	1.71	6.6	38.2	5,150
	L2	1.47	10.2	46.9	4,480
	L3	1.30	12.2	53.5	4,480
E-rated[4/]	E2.0T	2.0	3.2	26.2	7,350
	E1.8T	1.8	3.7	27.4	6,300
	E1.8C	1.8	7.2	39.2	6,300
Engelmann spruce[7/]					
Visually graded	L3	1.0	20	55	3,290
	No. 3	1.0	23	55.8	3,290
Lodgepole pine[4/]					
E-rated	E1.8T	1.8	6	34	6,300
	E1.5T	1.5	10	40	4,720
	E1.5C	1.5	15	45	4,720

1/ E = modulus of elasticity.

2/ $\bar{X}$ is average sum of knot sizes and h is the difference between the estimated near maximum and average sum of knot sizes.

3/ For L1, L2D, L2, L3 grades, E data are from AITC 117-74 (1), knot data from an industry-wide survey, and clear wood bending stress data obtained by multiplying values in USDA Bull. No. 1069 by 2.1 following adjustment to 10-year loading. For No. 3 grade, E from National Design Specification for lumber at 15 pct maximum moisture content, knot data assumed to be slightly larger than for L3, and clear wood bending stress assumed to be 80 pct of medium grain to account for possible occurrence of occasional wide-ringed material.

4/ Knot and clear wood bending stress data based on analysis of unpublished data supplied by Johnson for beams reported in (8,9).

5/ E is based on information collected in several previous studies on No. 2 medium grain lumber, knot data from partial results of an industry-wide survey, and clear wood bending stress obtained from USDA Bull. No. 1069 as described in footnote 3.

6/ E data from ASTM D 245 procedure and assuming a 5 pct increase if specific gravity greater than 0.39, knot data supplied by AITC, and clear wood bending stress data based on a 5 pct lower exclusion limit from ASTM D 2555 data adjusted to 12-inch deep, uniformly loaded condition. A 17 pct increase in bending stress was then assumed to apply to "dense" material having a specific gravity greater than 0.39.

7/ Same as footnote 6 except that knot data estimated.

APPENDIX II

Source and Properties of Lumber

Material Source

Douglas-fir

All of the visually graded Douglas-fir material was from stock available at a glulam manufacturing plant in the northern California area. It was graded following kiln drying at the plant using normal plant procedures according to the laminating grades *(23,24)*. The exception was the No. 3 material used for the inner laminations of group C. This material was graded as L3 except the following characteristics were permitted:

(a) Met No. 3 requirement for knots and slope-of-grain for Structural Light Framing except that knot holes were the same size as knots. All material meeting No. 2 Structural Light Framing was removed to assure the material would be representative of No. 3.

(b) Wane was permitted along either edge to a maximum of one-sixth of the wide face. This resulted in a central portion of the lumber equal to two-thirds the total width, which provided a continuous glue bond.

(c) White speck or a combination of white speck and a knot did not occupy more than one-half of the cross section.

Hereafter, this shall be referred to as No. 3, but bear in mind that it was subject to the above grading criteria. For all grades and species, no material meeting a higher grade was permitted in that grade for the test beams.

The E-rated Douglas-fir came from the Willamette Valley region of Oregon and was graded by a CLT-1 machine. The 2.2E Douglas-fir was machine graded with the machine set to select all material meeting or exceeding 2.2E. This lumber was sorted a second time with the machine set to select 2.4E material, which was then removed and not used for this study. For the material to be used on the tension side of beams, the edge knot requirement (one-fourth for 1650f-1.5E and one-sixth for higher grades) was imposed. Material not meeting the edge knot requirement but meeting L3 grade was used on the compression side.

The goal for describing the E-grades used in the test beams was as follows:

1. Average E of the grade as determined by the E-computer was to be at least 95 pct of the nominal value, i.e., the 2.0E material averaged at least 1.9 million lb/in.^{2}.

2. The E of at least 90 pct of the material exceeded the nominal grade less 200,000 lb/in.^{2}, i.e., 1.8 million lb/in.^{2} for a 2.0E material.

Hem-fir

The visually graded hem-fir material was obtained in the vicinity of Boise, Idaho, and was graded by a representative of the American Institute of Timber Construction to meet the laminating grade requirements *(23,24)*. It was selected at a lumber mill and its maximum moisture content checked during grading. Many pieces were found to exceed the maximum 16 pct moisture content desired and were therefore discarded. This sorting operation may have eliminated some of the heavier material which dried more slowly, thus biasing the sample toward the lighter and perhaps less stiff material. The degree, if any, to which this selection procedure affected the properties of the sample was impossible to determine. E-rated hem-fir was also obtained in Oregon using the same equipment and general principles used to obtain the Douglas-fir E-rated lumber.

Material used in beams D-03 and D-04 was anatomically identified as belonging to the white fir (Abies) group and was probably either grand fir or California red fir. Knowing it was purchased in the Boise, Idaho area suggested that it was grand fir (Abies grandis).

Midlength tension laminations for beams G-01, -02, -03, -05, and -10 were identified as belonging to the fir group. All of these five except G-10 were probably grand fir because they were purchased in Idaho; G-10, along with the second lamination of G-02, may have been white fir (Abies Concolor) from Oregon. Material used for the outer two tension laminations in beam G-11 was identified as belonging to the hemlock (Tsuga) group and, as it was purchased in Oregon, it was probably

western hemlock (Tsuga heterophylla). The other tension laminations were also identified as hemlock (Tsuga) and were likely western hemlock.

Southern pine

All of the southern pine began as a mixture of No. 1, No. 1D, No. 2D, and No. 2MG material at a glulam plant as graded according to southern pine rules *(19)*. Its origin was unknown. From one group, enough No. 2MG was sorted for the inner lamination of group F beams. E-rated material was obtained from a different group by use of E-computer. As southern pine was not readily available in E-grades or no commercial equipment could be found in a location convenient to the southern pine lumber industry, the E-grades for the outer lamination were selected using the E-computer. The MSR Douglas-fir and hem-fir lumber grades had been previously evaluated by the E-computer and their distribution form was used as a guideline.

Western woods

Visually graded Engelmann spruce was obtained from Colorado for the inner lamination of groups A, B, and H beams. L3 material for group H was graded according to the rules for laminating lumber *(22,23)*. No. 3 material was graded as previously described for Douglas-fir. Both L3 and No. 3 were obtained from Standard and Utility grade light framing material.

The tension laminations of beams H-02 and H-11 were anatomically identified as belonging to the pine (Pinus) group and were probably lodgepole (Pinus contorta). The wood's known source supports this. The inner laminations were identified as belonging to the spruce (Picea) group and it was purchased in Colorado as Engelmann spruce (Picea engelmannii).

E-rated material was obtained from lodgepole pine in central Oregon. As with the southern pine, it was necessary to simulate the E-grades. Rather than an E-computer, midspan deflections under a known weight were used as the criteria for selection. Edge knot criteria were followed, i.e., material for the tension side of beams had a maximum of one-fourth edge knot, while compression side material was permitted up to 50 pct knot as in L3. The lodgepole pine was selected from construction and standard light framing grade lumber.

LUMBER PROPERTIES

Properties of the various grades of lumber are summarized in table II-1, and midlength tension lamination data are given in table II-2.

Visual Grades

Visually graded Douglas-fir lumber was 10-25 pct stiffer than assumed while the visually graded hem-fir was 5-15 pct lower in stiffness than assumed. L2 and L3 grade Douglas-fir had smaller average knot size but larger near maximum knot sizes than assumed—the net effect probably being to cancel one another in their effect upon beam design. L1 hem-fir had a larger knot size than assumed which can be attributed to the specific selection of relatively low quality L1 pieces for tension lamination. L2 and L3 hem-fir had knot properties close to those assumed.

No. 2MG southern pine lumber had properties close to those assumed, while Engelmann spruce was slightly stiffer and had slightly smaller knot size.

E-Rated Grades

As expected, the E of all the E-rated grades was close to that assumed. Knot properties of both Douglas-fir and hem-fir were quite near those assumed for the material used on the tension side but the compression side material had a considerably higher near maximum knot size. It would appear that this material should be assumed to have knot properties similar to L3 material of the same species group.

The outer tension lamination southern pine material had a smaller near maximum sized knot than assumed but the other material was quite close. As with the Douglas-fir and hem-fir, the E-rated compression side material should probably be considered to have knot properties similar to the inner laminations (No.

2MG).

The outer tension lamination grade of the lodgepole pine had knot properties larger than assumed, probably due to the specific selection of low quality pieces. The other grade used as a second lamination was close to that assumed while the outer compression lamination had larger knots. As with the other species groups, the lodgepole pine pieces probably should be assumed to be similar to an L3 grade of the same species (15).

Tension Laminations

All tension laminations had significant strength reducing characteristics within the constant moment section (table II-2). Up to 0.3 feet may have been sawn from the ends of the beams during manufacture so that the location of characteristics might not correspond exactly with failure descriptions given in appendix III.

All measurements of knot size and amount of grain deviation were conducted prior to assembly of beams. It was obvious after the tests that the amount of grain deviation and slope-of-grain had been underestimated in several instances.

Table II-1.--Properties of lumber grades used in beam manufacture

Species group and grading method	Grade	Number of lumber pieces	Moisture content	Specific gravity	Modulus of elasticity		Knot data[1/]		
					Mean	Coefficient of variation	Lineal feet of 2 x 4 lumber measured	$\bar{X}$	h
			Pct		Million lb/in.^{2}	Pct	Ft	Pct	Pct
Douglas-fir									
Visually graded	L1	134	12	0.53	2.33	20.1	450	4.3	30.7
	L2D	138	12	.51	2.17	21.4	450	6.0	42.4
	L2	90	10	.49	2.02	18.6	900	5.4	55.3
	L3	237	12	.51	2.02	18.6	2,400	8.2	58.9
	No. 3	120	10	.47	1.84	19.7	--	--	--
E-rated	E2.2T	54	11	.48	2.24	4.0	300	6.3	36.5
	E2.0T	52	11	.47	2.08	3.9	300	8.4	36.6
	E2.0C	63	11	.51	2.08	5.9	300	9.7	58.8
Southern pine									
Visually graded	No. 2MG	180	--	--	1.53	17.8	900	8.6	49.1
E-rated	E2.0T	57	--	--	2.01	5.7	300	2.4	19.4
	E1.8T	56	--	--	1.79	5.7	300	5.6	41.5
	E1.8C	52	--	--	1.79	5.8	300	9.4	49.1
Hem-fir									
Visually graded	L1D	77	10	.39	1.62	12.5	150	11.2	38.1
	L2	92	9	.36	1.27	14.6	450	11.1	50.2
	L3	273	9	.36	1.20	14.8	1,500	13.0	54.1
E-rated	E2.0T	48	10	.45	2.22	7.8	150	5.4	23.9
	E1.8T	35	9	.41	1.88	3.6	150	5.6	35.4
	E1.8C	59	11	.43	1.88	3.8	300	9.9	52.7
Engelmann spruce									
Visually graded	L3	163	13	.40	1.20	14.9	750	16.0	45.4
	No. 3	342	11	.39	1.22	16.8	--	--	--
Lodgepole pine									
E-rated	E1.8T	45	10	.46	1.80	6.6	150	11.4	34.[illegible]
	E1.5T	36	10	.43	1.49	7.2	150	11.8	35.3
	E1.5C	58	10	.45	1.49	8.2	300	17.3	54.1

1/ $\bar{X}$ is average sum of knot sizes and h is the difference between the estimated near maximum and average sum of knot sizes.

Table II-2.--Data for midlength tension laminations

Beam No.	Lumber data				Critical knot			
	Length	Specific gravity[1/]	Moisture content[2/]	E[3/]	Location[4/]	Knot type[5/]	Knot size	Grain deviation
	Ft		Pct	Million lb/in.^{2}	Ft		Pct	Pct
				GROUP A--DOUGLAS-FIR				
A01	12	0.47	11	2.25	10.1-10.3	Ed	23	45
A02	12	.52	14	2.37	9.6	Ed	23	41
A03	10	.52	13	2.18	10.5	C	27	52
A04	14	.54	12	2.49	10.3	Ed	23	43
A05	14	.44	10	1.88	11.1	Ed	20	36
A06	8	.48	9	1.82	10.2	C	21	41
A07	16	.49	12	1.84	10.3	Ed	21	43
A08	16	.53	12	1.97	10.3	Ed	23	39
A09	14	.53	13	2.49	10.1	Ed	25	41
A10	14	.51	13	2.49	10.2	Ed	20	39
A11	16	.51	12	2.27	9.7	Ed	20	34
A12	10	.58	13	2.76	10.6	Ed	29	41
A13	10	.52	12	2.46	11.6	Ed	21	38
A14	14	.46	10	2.12	11.3	Ed	27	38
A15	10	.48	11	1.80	9.3	Ed	23	32
Average		.51	12	2.21	--	C-2	24	46
						Ed-13	23	39
				GROUP B--DOUGLAS-FIR				
B01	8	0.54	11	2.74	10.0	Ed	21	32
B02	14	.50	12	2.23	11.0	Ed	14	32
B03	14	.48	10	2.10	8.6	C	25	46
B04	14	.52	13	1.81	10.1	Ed	11	36
B05	16	.48	11	1.86	11.1	C	25	46
B06	16	.51	11	2.49	9.8	Ed	18	34
B07	14	.54	13	2.60	10.2	Ed	20	34
B08	14	.55	15	2.68	10.2	Ed	16	36
B09	16	.54	12	2.15	10.3	Ed	7	34
B10	14	.47	10	2.04	10.1	Ed	18	30
B11	14	.53	12	2.87	9.7	Ed	16	30
B12	14	.54	13	1.52	11.2	Ed	18	29
B13	14	.48	11	1.62	10.3	Ed	0	34
B14	16	.56	13	2.93	9.8	Ed	25	36
B15	10	.56	15	2.23	10.2	Ed	18	32
Average		.52	12	2.26	--	C-2	25	46
						Ed-13	16	33

Table II-2.--Data for midlength tension laminations--continued

Beam No.	Lumber data: Length	Specific gravity[1/]	Moisture content[2/]	E[3/]	Critical knot: Location[4/]	Knot type[5/]	Knot size	Grain deviation
	Ft		Pct	Million lb/in.^{2}	Ft		Pct	Pct
			GROUP C--DOUGLAS-FIR					
C01	14	0.52	10	2.02	9.8	Ed	23	30
C02	16	.50	11	1.92	9.0-9.2	Ed	20	43
C03	14	.51	13	2.10	9.1	Ed	25	36
C04	14	.49	11	1.94	10.0	Ed	29	39
C05	16	.52	13	1.72	10.4	Ed	29	39
C06	8	.46	9	1.87	9.6	C	29	43
C07	16	.53	11	2.43	9.2	Ed	20	34
C08	14	.50	11	1.88	10.5	Ed	20	41
C09	8	.48	10	1.71	10.6	C	25	43
C10	16	.52	11	2.08	10.8	Ed	20	30
C11	16	.49	10	2.30	9.0	Ed	16	27
C12	8	.49	10	1.87	9.4	Ed	20	34
C13	16	.50	13	2.10	9.2	Ed	21	34
C14	16	.47	12	1.74	10.2	Ed	29	41
C15	14	.50	10	1.49	9.9-10.2	Ed	21	38
Average		.50	11	1.94	--	C-2	27	43
						Ed-13	23	36
			GROUP D--HEM-FIR					
D01	16	0.40	18	1.65	10.1	C	25	38
D02	16	.39	13	1.83	9.5	C	21	36
D03	16	.39	12	1.79	10.2	Ed	27	41
D04	14	.37	14	1.43	10.0	C	27	41
D05	16	.40	13	1.93	10.0	Ed	29	43
D06	16	.38	13	1.66	9.9	C	34	50
D07	16	.39	13	1.41	10.2	Ed	27	41
D08	16	.39	12	1.78	10.6	C	34	48
D09	16	.39	15	1.60	9.6-10.0	Ed	21	38
D10	16	.39	13	1.39	11.0	C	21	32
D11	16	.39	14	1.49	10.5	Ed	27	39
D12	16	.37	14	1.59	9.8	C	27	36
D13	16	.41	15	1.78	10.1	C	29	45
D14	16	.40	12	1.46	10.0	Ed	16	38
D15	16	.40	14	1.66	10.2	C	27	45
Average		.39	14	1.63	--	C-9	27	41
						Ed-6	24	40

Table II-2.--Data for midlength tension laminations--continued

Beam No.	Lumber data: Length	Specific gravity[1/]	Moisture content[2/]	E[3/]	Critical knot: Location[4/]	Knot type[5/]	Knot size	Grain deviation
	Ft		Pct	Million lb/in.^{2}	Ft		Pct	Pct
				GROUP E--DOUGLAS-FIR				
E04	12	0.49	11	2.13	11.6	C	27	45
E05	12	.51	11	2.32	10.6-10.9	C	23	43
E08	12	.49	11	2.32	10.3	C	30	43
E09	12	.45	10	2.12	9.1-9.3	C	36	43
E10	12	.48	12	2.25	11.1	C	27	46
E12	12	.51	10	2.25	10.3	Ed	27	41
E15	12	.50	13	2.37	9.6	Ed	11	29
E16	12	.45	10	2.23	9.9	C	16	39
E19	12	.46	10	2.34	11.4	Ed	21	30
E21	12	.44	9	2.16	9.2	Ed	25	46
E24	14	.51	13	2.18	11.4	C	32	46
E26	12	.44	9	1.95	10.3	Ed	18	27
E27	16	.52	11	2.16	9.2	Ed	25	38
E28	12	.51	11	2.32	9.9	Ed	18	39
E29	12	.47	11	2.25	10.8	Ed	14	39
Average		.48	11	2.22	--	C-7	27	44
						Ed-8	20	36
				GROUP F--SOUTHERN PINE				
F02	14			1.77	9.8	C	11	32
F03	14			2.02	10.2	Ed	14	27
F04	14			1.81	9.3	C	12	36
F07	14			2.01	11.8	C	9	27
F08	14			2.16	9.8	Ed	9	27
F11	14			2.04	8.7	Ed	21	29
F12	14			2.20	9.5	Ed	14	29
F13	14			1.81	9.8	C	12	29
F17	14			2.12	10.1	C	12	34
F20	16			1.82	10.0	C	14	39
F21	14			1.97	10.2	Ed	18	32
F22	16			2.14	8.2	C	12	29
F23	14			2.03	8.9	Ed	11	34
F27	16			2.01	10.0	Ed	11	27
F28	14			2.18	10.0	C	21	38
Average				2.01	--	C-8	13	33
						Ed-7	14	29

Table II-2.--Data for midlength tension laminations--continued

Beam No.	Lumber data: Length	Specific gravity[1/]	Moisture content[2/]	E[3/]	Critical knot: Location[4/]	Knot type[5/]	Knot size	Grain deviation
	Ft		Pct	Million lb/in.^{2}	Ft		Pct	Pct
			GROUP G--HEM-FIR					
G01	16	0.40	10	1.74	9.8	Ed	18	25
G02	16	.38	12	1.86	10.0	C	12	22
G03	16	.37	10	1.76	10.0	C	27	34
G04	14	.41	12	2.10	10.0	C	16	27
G05	16	.38	13	1.80	10.0	Ed	18	27
G06	14	.39	12	2.16	10.1	Ed	18	25
G07	12	.42	13	2.03	10.0	C	18	30
G08	12	.42	10	2.04	10.0	Ed	11	27
G09	12	.47	14	2.24	8.1	Ed	18	32
G10	12	.41	12	2.11	10.0	C	20	32
G11	14	.41	9	1.97	10.0	Ed	16	29
G12	14	.45	12	2.19	10.1	C	18	30
G13	12	.45	14	1.91	10.1	Ed	16	27
G14	14	.45	12	2.09	10.2	Ed	18	32
G15	14	.40	13	1.99	10.3	Ed	16	29
Average		.41	12	2.00	--	C-6	18	29
						Ed-9	17	28
			GROUP H--LODGEPOLE PINE					
H01	12	0.47	12	1.71	9.8-10.2	C	25	38
H02	12	.42	12	1.87	10.1-10.3	Ed	30	46
H03	14	.44	11	1.83	10.1	Ed	25	36
H04	16	.41	11	1.88	10.1	C	23	38
H05	14	.49	11	1.92	10.1	C	14	38
H06	16	.43	11	1.72	10.0	C	21	32
H07	14	.42	11	1.86	10.0	C	23	39
H08	14	.44	11	1.59	9.1	Ed	25	32
H09	14	.43	11	1.70	9.9-10.0	Ed	32	48
H10	16	.44	13	1.80	10.9	Ed	25	36
H11	16	.45	11	1.76	11.2-11.7	C	21	30
H12	16	.43	11	1.78	11.0	C	21	41

Table II-2.--Data for midlength tension laminations--continued

Beam No.	Lumber data				Critical knot			
	Length	Specific gravity[1/]	Moisture content[2/]	E[3/]	Location[4/]	Knot type[5/]	Knot size	Grain deviation
	Ft		Pct	Million lb/in.^{2}	Ft		Pct	Pct
			GROUP H--LODGEPOLE PINE--cont.					
H13	14	0.44	11	1.65	10.0	C	29	43
H14	14	.41	10	1.62	10.7-11.0	Ed	30	45
H15	14	.49	11	2.03	11.0	Ed	20	34
Average		.44	11	1.78	--	C-8	22	37
						Ed-7	27	40

1/ Based on ovendry weight and volume at time of test.

2/ Average of three values taken with a surface-type meter.

3/ Modulus of elasticity determined with an E-computer.

4/ Location of defect in beam measured from reference end of beam.

5/ Edge (Ed) or centerline (C).

APPENDIX III

Beam Test Results

Table III-1.--Results of bending tests

Beam No.	Dimensions[1/] Width	Dimensions[1/] Depth	Moisture content[2/]	Specific gravity[3/]	Modulus of rupture	Modulus of elasticity: Full span	Modulus of elasticity: Constant moment section	Shear stress at failure	Failure comments[4/]: Selected tension lamination knot	Failure comments[4/]: Tension lamination finger joint	Failure comments[4/]: Other
	In.	In.	Pct		Lb/in.^{2}	Million lb/in.^{2}	Million lb/in.^{2}	Lb/in.^{2}			
				GROUP A:	OUTER LAMINATIONS--VISUALLY GRADED DOUGLAS-FIR, INNER LAMINATIONS--NO. 3 ENGELMANN SPRUCE						
A01	3.08	12.38	9	0.45	6,550	1.64	1.80	225	MAJ. at 10.1		
A02	3.07	12.36	9	.47	7,720	1.72	1.85	265	MAJ. at 9.8		
A03	3.07	12.39	10	.50	6,000	1.83	1.87	207		10 pct at 6.0	S.O.G. 4 to 6
A04	3.07	12.39	11	.45	4,260	1.96	2.07	147		40 pct at 8.6	S.O.G.
A05	3.08	12.40	11	.43	3,450	1.73	1.84	119			Shear
A06	3.08	12.37	8	.47	4,560	1.85	1.78	157	INV.		S.O.G. 8 to 11
A07	3.09	12.37	10	.44	5,590	1.76	1.85	192		MAJ. at 7.5	
A08	3.08	12.38	10	.46	4,830	1.94	2.04	166	MAJ. at 10.0		
A09	3.08	12.38	9	.47	5,780	1.97	1.99	199		MAJ. at 4.0	
A10	3.09	12.40	11	.46	4,920	1.93	2.39	169		MAJ. at 8.0	
A11	3.08	12.39	10	.44	4,940	1.58	1.77	170	MAJ. at 9.3		
A12	3.09	12.39	10	.44	3,190	1.75	2.13	110		MAJ. at 9.2	
A13	3.08	12.43	9	.46	5,350	1.73	1.88	185			G.D. at 9.5
A14	3.08	12.39	10	.44	3,860	1.72	1.79	133		MAJ. at 9.2	
A15	3.08	12.38	9	.47	4,520	1.82	1.98	155			G.D. at 11.4
Av.	3.08	12.39	10	.46	5,040	1.80	1.94	173			
C.O.V.[5/]					23.7	6.6	8.8	--			
				GROUP B:	OUTER LAMINATIONS--VISUALLY GRADED DOUGLAS-FIR, INNER LAMINATIONS--NO. 3 ENGELMANN SPRUCE						
B01	3.07	17.86	9	0.47	6,280	2.04	2.20	312	MAJ. at 10.0		
B02	3.08	17.91	10	.46	6,460	1.83	1.95	322		MAJ. at 8.5	
B03	3.08	17.90	10	.45	4,670	1.71	1.68	232	MAJ. at 8.8		
B04	3.09	17.92	10	.46	4,440	1.63	1.63	221	MAJ. at 10.1		
B05	3.09	17.90	10	.46	5,690	1.60	1.86	283	MAJ. at 9.8		G.D. at 9.0
B06	3.08	17.89	10	.46	6,080	1.97	1.86	302	MAJ. at 9.8		
B07	3.08	17.86	8	.46	6,710	1.79	2.16	333	MAJ. at 10.2		
B08	3.08	17.89	10	.47	4,720	1.72	1.79	235		MAJ. at 9.1	
B09	3.08	17.91	10	.46	5,620	1.67	1.68	279	MAJ. at 10.0		
B10	3.07	17.86	10	.47	5,660	1.78	1.71	281			Shear
B11	3.08	17.91	10	.48	6,310	1.89	2.12	314		MAJ. at 10.5	
B12	3.07	17.90	10	.46	4,030	1.58	1.55	201		5 pct at 13.1	G.D. at 12.5
B13	3.07	17.86	10	.47	5,170	1.59	1.66	256	MAJ. at 10.0		
B14	3.06	17.88	10	.50	5,810	2.09	2.15	289		MAJ. at 4.4	
B15	3.07	17.91	10	.47	5,780	1.79	1.97	288		1 pct at 10.3	S.O.G. 10 to 12
Av.	3.08	17.89	10	.47	5,560	1.78	1.87	276			
C.O.V.[5/]					14.3	9.1	11.6	--			

Table III-1.--Results of bending tests--continued

Beam No.	Dimensions[1/] Width	Dimensions[1/] Depth	Moisture content[2/]	Specific gravity[3/]	Modulus of rupture	Modulus of elasticity: Full span	Modulus of elasticity: Constant moment section	Shear stress at failure	Failure comments[4/]: Selected tension lamination knot	Failure comments[4/]: Tension lamination finger joint	Failure comments[4/]: Other
	In.	In.	Pct		Lb/in.²	Million lb/in.²	Million lb/in.²	Lb/in.²			
				GROUP C:	OUTER LAMINATIONS--VISUALLY GRADED DOUGLAS-FIR, INNER LAMINATIONS--NO. 3 DOUGLAS-FIR						
C01	3.07	17.91	9	0.48	6,270	1.83	1.90	312	MAJ. at 9.6		
C02	3.08	17.88	9	.49	5,890	1.88	2.00	292	MAJ. at 9.1		
C03	3.08	17.91	9	.50	6,770	1.79	1.86	337	MAJ. at 8.9		
C04	3.08	17.88	8	.49	5,990	1.79	1.70	298	MAJ. at 10.1		
C05	3.08	17.89	9	.50	5,900	1.78	1.61	293	MAJ. at 10.0		
C06	3.06	17.86	9	.50	5,230	1.83	2.10	260			S.O.G. 7 to 9
C07	3.08	17.90	9	.50	5,960	1.89	2.15	296	MAJ. at 9.2		
C08	3.08	17.89	9	.50	7,770	1.92	1.87	386	INV. at 10.4	10 pct at 9.5	S.O.G.
C09	3.08	17.88	10	.47	5,670	1.67	1.54	282			S.O.G. 7 to 9
C10	3.07	17.89	9	.48	6,860	1.76	1.68	341	MAJ. at 10.7		
C11	3.07	17.87	9	.49	5,320	1.93	2.06	264	MAJ. at 9.0		
C12	3.08	17.86	10	.49	6,180	1.89	1.91	306			S.O.G. 8 to 11
C13	3.07	17.91	9	.50	6,240	1.77	1.77	311			G.D. at 7.3
C14	3.08	17.91	9	.49	3,500	1.83	1.57	174	MAJ. at 10.0		
C15	3.07	17.91	10	.47	4,600	1.58	1.57	229			G.D. at 7.5
Av.	3.08	17.89	9	.49	5,880	1.81	1.82	292			
C.O.V.[5/]					16.9	5.2	11.2	--			
				GROUP D:	OUTER LAMINATIONS--VISUALLY GRADED HEM-FIR, INNER LAMINATIONS--L3 HEM-FIR						
D01	3.06	12.41	10	0.37	5,250	1.37	1.38	181		MAJ. at 9.5	
D02	3.06	12.37	9	.36	4,720	1.30	1.35	162			G.D. at 13.0
D03	3.06	12.39	9	.38	5,750	1.38	1.43	198	MAJ. at 9.9		G.D. at 8.5
D04	3.07	12.39	9	.38	4,920	1.35	1.41	170		30 pct at 13.7	S.O.G. 10 to 14
D05	3.06	12.37	10	.38	5,720	1.28	1.29	197	MAJ. at 9.9		G.D. at 10.6
D06	3.08	12.40	10	.38	4,550	1.30	1.46	157	MAJ. at 9.8		
D07	3.07	12.39	9	.39	4,720	1.24	1.39	163			G.D. at 11.9
D08	3.08	12.39	9	.36	4,230	1.37	1.53	146	MAJ. at 10.5		
D09	3.07	12.35	9	.37	5,360	1.20	1.32	184			Compression
D10	3.08	12.40	10	.37	4,510	1.29	1.34	155		MAJ. at 8.8	
D11	3.07	12.38	9	.38	4,820	1.22	1.40	166	MAJ. at 10.3		
D12	3.08	12.39	10	.37	6,210	1.39	1.41	214			Compression
D13	3.07	12.36	9	.38	6,310	1.38	1.31	216			Compressi
D14	3.08	12.39	10	.37	4,790	1.24	1.33	165			Compression
D15	3.09	12.39	9	.39	4,710	1.32	1.20	162	MAJ. at 9.9		
Av.	3.07	12.39	9	.37	5,110	1.31	1.37	176			
C.O.V.[5/]					12.4	4.8	5.6	--			

Table III-1.--Results of bending tests--continued

Beam No.	Dimensions[1/] Width	Dimensions[1/] Depth	Moisture content[2/]	Specific gravity[3/]	Modulus of rupture	Modulus of elasticity: Full span	Modulus of elasticity: Constant moment section	Shear stress at failure	Failure comments[4/]: Selected tension lamination knot	Failure comments[4/]: Tension lamination finger joint	Failure comments[4/]: Other
	In.	In.	Pct		Lb/in.^{2}	Million lb/in.^{2}	Million lb/in.^{2}	Lb/in.^{2}			
					GROUP E: OUTER LAMINATIONS--E-RATED DOUGLAS-FIR, INNER LAMINATIONS--L3 DOUGLAS-FIR						
E04	3.07	12.38	11	0.49	5,120	1.91	1.90	176	MAJ. at 11.7		
E05	3.09	12.40	12	.51	5,300	2.02	2.32	183		MAJ. at 8.7	
E08	3.08	12.40	8	.52	6,760	1.98	2.14	233		40 pct at 9.1	S.O.G. 8 to 9
E09	3.07	12.40	10	.52	6,110	2.02	2.22	210		90 pct at 12.5	S.O.G.
E10	3.07	12.40	10	.51	7,250	2.04	2.14	250	MAJ. at 11.0		G.D. 9 to 10
E12	3.09	12.40	11	.50	6,420	1.97	1.81	221	MAJ. at 10.1		G.D. at 8.4
E15	3.08	12.39	10	.53	5,500	2.26	2.37	189		50 pct at 10.2	G.D. at 9.6
E16	3.06	12.40	10	.51	6,990	2.22	2.40	241	INV. at 9.8	5 pct at 7.4	
E19	3.07	12.41	11	.54	5,820	2.21	2.48	201	MAJ. at 11.5		S.O.G. 8 to 11
E21	3.08	12.42	10	.52	5,680	1.98	2.20	196	MAJ. at 9.1		
E24	3.08	12.39	10	.54	5,220	1.96	2.12	180			G.D. 9 to 10
E26	3.08	12.39	10	.55	5,690	2.07	2.48	196		MAJ. at 6.1	
E27	3.08	12.40	12	.56	5,140	1.97	2.02	177	MAJ. at 9.1		
E28	3.08	12.40	10	.50	6,800	1.86	1.96	234	MAJ. at 9.7		G.D. at 11.2
E29	3.09	12.32	12	.53	8,740	2.21	2.32	299	INV. at 10.8		S.O.G. 6 to 11
Av.	3.08	12.39	10	.52	6,170	2.05	2.19	212			
C.O.V.[5/]					16.3	6.0	9.4	--			
					GROUP F: OUTER LAMINATIONS--E-RATED SOUTHERN PINE, INNER LAMINATIONS--NO. 2MG SOUTHERN PINE						
F02	3.11	12.33	11	0.53	8,380	1.73	1.96	287	MAJ. at 9.6		
F03	3.13	12.34	10	.51	7,060	1.72	2.07	242	MAJ. at 9.9		
F04	3.15	12.37	10	.50	7,280	1.70	1.99	250		MAJ. at 8.1	
F07	3.11	12.40	10	.49	6,530	1.65	1.78	225		MAJ. at 13.2	
F08	3.11	12.38	12	.51	7,040	1.80	1.89	242		MAJ. at 12.8	
F11	3.11	12.32	11	.48	5,620	1.60	1.73	192	INV. at 8.5	30 pct at 7.5	
F12	3.14	12.32	10	.49	6,500	1.69	1.98	223		MAJ. at 11.6	
F13	3.14	12.31	10	.51	7,310	1.67	1.81	250		10 pct at 7.0	G.D. at 8.0
F17	3.15	12.35	12	.50	5,900	1.70	1.94	202		5 pct at 13.5	S.O.G. 12 to 1
F20	3.14	12.36	11	.49	5,420	1.62	1.67	186		MAJ. at 11.8	
F21	3.17	12.37	12	.51	4,800	1.75	1.95	165	MAJ. at 10.0		
F22	3.17	12.37	13	.48	4,780	1.67	2.17	164		MAJ. at 9.3	
F23	3.18	12.35	11	.49	6,890	1.55	2.04	236		20 pct at 12.2	G.D. 12 to 13
F27	3.14	12.36	11	.50	8,710	1.77	2.05	299	MAJ. at 9.8		G.D. at 9.0
F28	3.13	12.33	11	.50	6,660	1.74	1.83	228	MAJ. at 9.8		
Av.	3.14	12.35	11	.50	6,590	1.69	1.92	226			
C.O.V.[5/]					17.4	4.0	7.2	--			

Table III-1.--Results of bending tests--continued

Beam No.	Dimensions[1/] Width	Dimensions[1/] Depth	Moisture content[2/]	Specific gravity[3/]	Modulus of rupture	Modulus of elasticity: Full span	Modulus of elasticity: Constant moment section	Shear stress at failure	Failure comments[4/]: Selected tension lamination knot	Failure comments[4/]: Tension lamination finger joint	Failure comments[4/]: Other
	In.	In.	Pct		Lb/in.^{2}	Million lb/in.^{2}	Million lb/in.^{2}	Lb/in.^{2}			
GROUP G: OUTER LAMINATIONS--E-RATED HEM-FIR, INNER LAMINATIONS--L3 HEM-FIR											
G01	3.09	12.40	9	0.40	3,810	1.66	1.79	131	MAJ. at 9.6		G.D. at 12.5
G02	3.09	12.39	8	.40	5,450	1.69	1.86	188	MAJ. at 9.7		
G03	3.09	12.41	9	.39	6,480	1.71	2.04	224		MAJ. at 8.3	
G04	3.08	12.36	9	.40	6,340	1.72	2.09	218			S.O.G. 9 to 13
G05	3.07	12.39	9	.40	5,440	1.75	1.73	187	MAJ. at 10.1		
G06	3.08	12.38	9	.40	6,610	1.73	2.04	227		80 pct at 6.4	S.O.G.
G07	3.08	12.37	9	.41	7,850	1.69	1.69	270			Compression
G08	3.07	12.36	9	.40	6,890	1.71	1.84	237			Compression
G09	3.08	12.36	8	.42	7,290	1.73	1.81	250			S.O.G. 6 to 8
G10	3.07	12.37	8	.41	6,140	1.72	1.83	211		MAJ. at 8.3	
G11	3.07	12.37	9	.40	5,600	1.70	1.78	192		MAJ. at 8.4	
G12	3.08	12.42	10	.39	6,170	1.65	1.71	213		MAJ. at 9.4	
G13	3.08	12.40	10	.40	6,730	1.61	1.81	232			Compression
G14	3.08	12.40	9	.40	6,640	1.71	1.84	229	MAJ. at 10.0		
G15	3.08	12.29	9	.40	5,690	1.78	1.80	194	INV. at 10.1	60 pct at 9.0	
Av.	3.08	12.38	9	.40	6,210	1.70	1.84	214			
C.O.V.[5/]					15.3	2.4	6.6	--			
GROUP H: OUTER LAMINATIONS--E-RATED WHITE WOOD (LODGEPOLE PINE), INNER LAMINATIONS--L3 WHITE WOOD (ENGFIMANN SPRUCE)											
H01	3.06	12.33	10	0.43	7,580	1.45	1.52	260			Compression
H02	3.06	12.36	10	.42	6,430	1.44	1.66	221	INV. at 10.0		G.D. at 11.5
H03	3.08	12.38	11	.41	4,540	1.48	1.54	156	INV. at 9.9	40 pct at 9.0	
H04	3.07	12.35	10	.43	5,490	1.38	1.54	188		MAJ. at 8.2	
H05	3.07	12.35	10	.42	5,480	1.45	1.65	188			Compression
H06	3.08	12.36	11	.42	4,500	1.37	1.44	154		MAJ. at 8.8	
H07	3.07	12.34	9	.43	5,440	1.47	1.58	186			G.D. at 10.6
H08	3.08	12.34	9	.43	4,420	1.36	1.50	152	MAJ. at 9.2		
H09	3.09	12.38	9	.43	4,510	1.38	1.57	155	MAJ. at 10.0		
H10	3.08	12.38	11	.42	4,400	1.45	1.58	152	MAJ. at 10.9		G.D. at 11.5
H11	3.08	12.35	11	.41	5,790	1.34	1.39	199	MAJ. at 11.2		
H12	3.09	12.37	10	.43	6,360	1.51	1.74	218			Compression
H13	3.09	12.38	9	.43	4,300	1.40	1.51	148	MAJ. at 9.9		
H14	3.08	12.39	10	.42	4,240	1.34	1.44	146		MAJ. at 7.0	
H15	3.08	12.39	10	.42	4,780	1.51	1.71	164	MAJ. at 10.8		G.D. at 9.4
Av.	3.08	12.37	10	.42	5,220	1.42	1.56	179			
C.O.V.[5/]					18.9	4.1	6.4	--			

1/ Dimensions are averages of measurements made at--and 4 ft both sides of--midlength.

2/ Determined immediately following test using a resistance-type meter with 1-1/2-in.-long needles. Data given are averages of readings taken for each lamination at point of failure. Readings were corrected using factors published by the manufacturer.

3/ Based on weight and volume of complete beam at time of test. Weight was adjusted to ovendry.

4/ Locations are given in feet with reference to one end of the beam. Midlength was at 10.0 and constant moment section was from 8.0 to 12.0. MAJ. = major cause; INV. = involved in failure; S.O.G. = slope of grain; and G.D. = grain deviation.

5/ Coefficient of variation = (standard deviation ÷ average) x 100.

APPENDIX IV

Determination of Clear Wood Bending Stress (CWS) Value from Beam Test Data

To attain CWS values for different species and grades of lumber, data from past experiments conducted at FPL, Oregon State University, and both Canadian Laboratories were analyzed. Strength ratios were estimated by the I_K/I_G concept using knot data obtained either from analysis of the lumber used or from similarly graded lumber. Strength ratios were expressed as the ratio of the anticipated near minimum strength to that of a clear beam consisting entirely of the density and/or stiffness of material in the tension lamination. Based on concepts discussed in this report:

$$MOR = (CWS)(SR)\left(\frac{Td}{2z}\right)$$

MOR - expected near minimum beam strength

CWS - expected near minimum clear wood stress for tension lamination quality material

SR - strength ratio

t - transformed section factor

d/2z - ratio of half depth to neutral axis positions.

By redefining SR as

$$(SR)_{Eff} = (SR)\left(\frac{Th}{2z}\right)$$

clear wood design stress can be expressed as

$$CWS = \frac{MOR}{(SR)_{Eff}}$$

Values of CWS were calculated for all beam tests for which strength ratios could be estimated.

MOR values were adjusted to a 12-in. common depth, a 21:1 span-to-depth ratio and uniform loading, and a 12 pct moisture content (ASTM D 2915). Also, the dead load stresses of the beams were added if they were not considered in the initial analysis.

Strength ratios calculated using the unbalanced I_K/I_G concept are included in table IV-1. Also, the strength ratio as believed to be limited by the tension lamination grade is included. The lower of these two strength ratios was multiplied by $\frac{Td}{2z}$ to determine the effective strength ratio. CWS values were thus calculated for each beam and are given in table IV-2. Each group was then statistically analyzed and results presented in the form of averages and standard deviations (table IV-3).

Table IV-1.--Beam groups used in clear wood stress analysis

Source	Beam identification	Number of beams	Tension side strength ratio: Knots[1/]	Tension side strength ratio: Tension lamination[2/]	Td/2z[3/]	Effective strength ratio[4/]
		VISUALLY GRADED DOUGLAS-FIR				
Present study	A01-A15	15	0.734	0.674	0.858	0.578
	B01-B15	15	.761	.724	.857	.620
	C01-C15	15	.756	.724	.865	.626
FPL 113	1,3,6-10	7	.735	.774	.934	.686
	2,4,5	3	.735	[2/] .674	.934	.630
	21-23	3	.770	.824	.934	.719
FPL 146	41-45	5	.735	.774	.934	.686
	46-50	5	.739	.774	.935	.691
FPL 236 (15)	86-90	5	.633	.674	.843	.534
	91-95	5	.637	.674	.928	.591
	96-105	10	.737	.774	.922	.680
Total	--	88	--	--	--	--
		VISUALLY GRADED SOUTHERN PINE				
FPL 113	11-20	10	.791	.674	.865	.583
FPL 113	24-26	3	.819	.774	.838	.649
FPL 146	36-40	5	.822	.774	.877	.679
FPL 151	51-60	10	.822	.774	.877	.679
Total	--	28	--	--	--	--
		VISUALLY GRADED HEM-FIR				
Present study	D01-D15	15	.589	.674	.894	.527
RP 18 (10)	Comb. 1	5	.732	.814	.930	.681
	Comb. 2	5	.718	.724	.901	.647
	Comb. 3	5	.718	.674	.897	.604
Total	--	30	--	--	--	--
		E-RATED DOUGLAS-FIR (2.4-2.6E TENSION LAMINATION)				
T-26 (9)	D01-D05	5	.766	.724	.887	.642
	D06-D11	6	.844	.724	.918	.665
T-27 (8)	D01-D06	6	.829	.774	.898	.695
Total	--	17	--	--	--	--

Table IV-1.--Beam groups used in clear wood stress analysis

Source	Beam identification	Number of beams	Tension side strength ratio: Knots[1/]	Tension side strength ratio: Tension lamination[2/]	Td/2z[3/]	Effective strength ratio[4/]
			E-RATED DOUGLAS-FIR (2.2E TENSION LAMINATION)			
Present study	E04-E29	15	.686	.724	.898	.616
T-27 (8)	D07-D12	6	.696	.724	.933	.649
Total	--	21	--	--	--	--
			E-RATED SOUTHERN PINE (2.2E TENSION LAMINATION)			
T-27 (8)	SP07-SP12	6	.766	.774	.901	.690
			E-RATED SOUTHERN PINE (2.0E TENSION LAMINATION)			
Present study	F02-F28	15	.752	.774	.900	.677
T-27 (8)	SP01-SP06	6	.770	.724	.933	.675
Total	--	21	--	--	--	--
			E-RATED HEM-FIR (2.0E TENSION LAMINATION)			
Present study	G01-G15	15	.771	.824	.895	.690
T-26 (9)	H01-H06	6	.870	.824	.965	.795
	W01-W06	6	.871	.824	.896	.738
T-27 (8)	HDF13-HDF18	6	.860	.774	.933	.722
	H19-H24	6	.855	.774	.927	.717
Total	--	39	--	--	--	--
			E-RATED HEM-FIR (1.8E TENSION LAMINATION)			
T-27 (8)	H25-H30	6	.848	.724	.916	.663
			E-RATED "WHITE WOODS" (2.4E TENSION LAMINATION)			
VP-X-132 (12)	9,11	4	.825	.824	.862	.710
			E-RATED "WHITE WOODS" (2.2E TENSION LAMINATION)			
VP-X-132 (12)	7,12	4	.747	.774	.861	.643

Table IV-1.--Beam groups used in clear wood stress analysis

Source	Beam identification	Number of beams	Tension side strength ratio: Knots 1/	Tension side strength ratio: Tension lamination 2/	$Td/2z$ 3/	Effective strength ratio 4/
		E-RATED "WHITE WOODS" (2.0E TENSION LAMINATION)				
VP-X-132 (12)	3,4	4	.729	.774	.920	.670
	8,10	4	.768	.774	.905	.695
Aplin (6)	A1-A8,B1-B8	14	.715	.824	.952	.681
	D1-D8	7	.802	.824	.955	.766
	E2-E8	6	.801	.824	.937	.751
Total	--	35	--	--	--	--
		E-RATED "WHITE WOODS" (1.8E TENSION LAMINATION)				
Present study	H01-H15	15	.640	.674	.848	.543
T-27 (8)	LP31-LP36	6	.659	.724	.911	.600
VP-X-132 (12)	1,2,5,6	8	.649	.774	.909	.590
Total	--	29	--	--	--	--
		E-RATED "WHITE WOODS" (1.6E TENSION LAMINATION)				
T-27 (8)	LP37-LP42	6	.633	.674	.897	.549

1/ Based on unbalanced I_K/I_G analysis using knot data either from lumber used in manufacture or similarly graded lumber. Tension side assumed to control.

2/ Estimated limiting strength ratio for outer tension lamination.

3/ Transformed section factor--see "Development of Design Criteria" in main text of this report.

4/ Lowest tension-side strength ratio multiplied by transformed section factor.

Table IV-2.--Adjusted modulus of rupture (MOR) and clear wood stress (CWS) values for glued, laminated beams

Beam identification	Adjusted MOR[1/]	Calculated CWS	Beam identification	Adjusted MOR[1/]	Calculated CWS	Beam identification	Adjusted MOR[1/]	Calculated CWS
	$Lb/in.^2$	$Lb/in.^2$		$Lb/in.^2$	$Lb/in.^2$		$Lb/in.^2$	$Lb/in.^2$
VISUALLY GRADED DOUGLAS-FIR			VISUALLY GRADED DOUGLAS-FIR--continued			VISUALLY GRADED DOUGLAS-FIR--continued		
A01	6,200	10,730	C01	6,050	9,660	41	7,080	10,320
A02	7,300	12,640	C02	5,680	9,070	42	5,050	7,360
A03	5,820	10,070	C03	6,520	10,410	43	6,010	8,760
A04	4,250	7,360	C04	5,650	9,020	44	5,940	8,650
A05	3,450	5,980	C05	5,690	9,090	45	6,460	9,420
A06	4,240	7,340	C06	5,050	8,070	46	7,170	10,370
A07	5,430	9,390	C07	5,740	9,170	47	3,920	5,670
A08	4,690	8,120	C08	7,480	11,950	48	5,900	8,550
A09	5,480	9,480	C09	5,600	8,950	59	5,360	7,760
A10	4,890	8,470	C10	6,610	10,560	50	6,180	8,950
A11	4,810	9,320	C11	5,130	8,200			
A12	3,120	5,400	C12	6,090	9,730	86	4,570	8,550
A13	5,080	8,780	C13	6,020	9,610	87	4,850	9,080
A14	3,770	6,510	C14	3,390	5,420	88	4,710	8,810
A15	4,290	7,430	C15	4,550	7,270	89	5,230	9,800
						90	5,640	10,560
B01	6,050	9,760	1	6,200	9,050	91	4,610	7,800
B02	6,380	10,280	3	5,840	8,520	92	6,270	10,610
B03	4,610	7,440	6	6,250	9,100	93	5,930	10,030
B04	4,390	7,090	7	5,840	8,510	94	4,670	17,910
B05	5,620	9,060	8	6,110	8,900	95	4,680	7,910
B06	6,000	9,670	9	6,380	9,300			
B07	6,320	10,190	10	5,310	7,730	96	6,170	9,080
B08	4,670	7,530	2	5,520	8,760	97	6,900	10,150
B09	5,550	8,940	4	4,600	7,300	98	5,880	8,640
B10	5,590	9,020	5	4,910	7,790	99	5,140	7,550
B11	6,230	10,040				100	5,830	8,570
B12	3,990	6,440	21	5,960	8,290	101	5,940	8,730
B13	5,100	8,230	22	5,760	8,000	102	6,100	8,970
B14	5,740	9,250	23	6,470	9,000	103	5,950	9,750
B15	5,710	9,200				104	5,620	8,270
						105	7,000	10,290
VISUALLY GRADED SOUTHERN PINE			VISUALLY GRADED SOUTHERN PINE--continued			VISUALLY GRADED SOUTHERN PINE--continued		
11	5,370	9,220	24	5,790	8,920	51	8,040	11,850
12	6,800	11,660	25	5,190	8,000	52	7,270	10,710
13	5,410	9,270	26	5,420	8,350	53	7,410	10,910
14	4,390	7,530				54	8,430	12,420
15	5,380	9,230	36	7,400	10,900	55	8,230	12,120
16	4,540	7,790	37	8,220	12,110	56	7,610	11,210
17	4,920	8,440	38	9,530	14,030	57	7,670	11,290
18	7,940	13,620	39	8,690	12,800	58	7,720	11,370
19	5,330	9,140	40	8,930	13,160	59	8,330	12,270
20	7,050	12,100				60	7,870	11,590
VISUALLY GRADED HEM-FIR			VISUALLY GRADED HEM-FIR--continued			VISUALLY GRADED HEM-FIR--continued		
D01	5,090	9,660	D11	4,570	8,670	2-1	4,800	7,420
D02	4,480	8,500	D12	6,010	11,410	2-2	5,140	7,940
D03	5,440	10,330	D13	5,960	11,320	2-3	4,620	7,130
D04	4,670	8,860	D14	4,650	8,820	2-4	4,460	6,890
D05	5,540	10,520	D15	4,470	8,480	2-5	5,370	8,300
D06	4,420	8,390						
D07	4,480	8,500	1-1	6,720	9,870	3-1	5,770	9,550
D08	4,020	7,620	1-2	7,200	10,570	3-2	5,230	8,660
D09	5,080	9,640	1-3	6,820	10,010	3-3	6,190	10,250
D10	4,380	8,310	1-4	5,210	7,650	3-4	5,770	9,550
			1-5	7,000	10,270	3-5	3,890	6,440

Table IV-2.--Adjusted modulus of rupture (MOR) and clear wood stress (CWS) values for glued, laminated beams--continued

Beam identification	Adjusted MOR[1/]	Calculated CWS	Beam identification	Adjusted MOR[1/]	Calculated CWS	Beam identification	Adjusted MOR[1/]	Calculated CWS
	$Lb/in.^2$	$Lb/in.^2$		$Lb/in.^2$	$Lb/in.^2$		$Lb/in.^2$	$Lb/in.^2$
E-RATED DOUGLAS-FIR (2.4-2.6E TENSION LAMINATION)			E-RATED DOUGLAS-FIR (2.4-2.6E TENSION LAMINATION)--continued			E-RATED DOUGLAS-FIR (2.4-2.6E TENSION LAMINATION)--continued		
D01	5,990	9,330	D06	6,810	10,250	D01	8,080	11,620
D02	7,440	11,580	D07	6,210	9,340	D02	8,360	12,020
D03	4,990	7,780	D08	5,940	8,930	D03	8,150	11,730
D04	8,080	12,580	D09	6,000	9,030	D04	8,550	12,300
D05	7,370	11,480	D10	8,360	12,570	D05	5,270	7,580
			D11	8,180	12,300	D06	6,670	9,590
E-RATED DOUGLAS-FIR (2.2E TENSION LAMINATION)			E-RATED DOUGLAS-FIR (2.2E TENSION LAMINATION)--continued			E-RATED DOUGLAS-FIR (2.2E TENSION LAMINATION)--continued		
E04	5,090	8,270	E19	5,780	9,380	D07	5,140	7,920
E05	5,400	8,770	E21	5,510	8,940	D08	7,440	11,470
E08	6,260	10,160	E24	5,070	8,240	D09	5,300	8,170
E09	5,930	9,620	E26	5,520	8,960	D10	5,860	9,020
E10	7,020	11,390	E27	5,240	8,510	D11	6,510	10,040
E12	6,370	10,340	E28	5,240	8,510	D12	5,780	8,900
E15	5,340	8,670	E29	8,870	14,400			
E16	6,770	11,000						
E-RATED SOUTHERN PINE (2.2E TENSION LAMINATION)			E-RATED SOUTHERN PINE (2.2E TENSION LAMINATION)--continued			E-RATED SOUTHERN PINE (2.2E TENSION LAMINATION)--continued		
SP07	6,430	9,320	SP09	9,040	13,100	SP11	6,490	9,410
SP08	6,900	10,000	SP10	7,110	10,300	SP12	7,150	10,360
E-RATED SOUTHERN PINE (2.0E TENSION LAMINATION)			E-RATED SOUTHERN PINE (2.0E TENSION LAMINATION)--continued			E-RATED SOUTHERN PINE (2.0E TENSION LAMINATION)--continued		
F02	8,310	12,270	F17	6,000	8,870	SP01	5,570	8,250
F03	6,830	10,090	F20	5,390	7,960	SP02	6,000	8,880
F04	7,050	10,410	F21	4,900	7,240	SP03	7,340	10,870
F07	6,330	9,350	F22	5,000	7,390	SP04	7,320	10,850
F08	7,160	10,570	F23	6,830	10,100	SP05	8,300	12,300
F11	5,580	8,250	F27	8,630	12,740	SP06	7,410	10,970
F12	6,300	9,310	F28	6,610	9,770			
F13	7,080	10,450						
E-RATED HEM-FIR (2.0E TENSION LAMINATION)			E-RATED HEM-FIR (2.0E TENSION LAMINATION)--continued			E-RATED HEM-FIR (2.0E TENSION LAMINATION)--continued		
G01	3,620	5,250	H01	7,240	9,110	HDF13	7,890	10,930
G02	5,050	7,310	H02	8,160	10,270	HDF14	7,150	9,900
G03	6,130	8,890	H03	8,880	11,160	HDF15	7,710	10,680
G04	6,000	8,690	H04	8,240	10,370	HDF16	6,750	9,350
G05	5,150	7,470	H05	8,670	10,900	HDF17	6,810	9,430
G06	6,250	9,060	H06	8,240	10,360	HDF18	8,020	11,100
G07	7,420	10,750						
G08	6,510	9,440	W01	7,340	9,940	H19	5,900	8,230
G09	6,730	9,760	W02	6,740	9,130	H20	6,920	9,650
G10	5,680	8,240	W03	7,340	9,940	H21	6,680	9,310
G11	5,300	7,680	W04	6,840	9,270	H22	7,090	9,890
G12	5,970	8,650	W05	7,110	9,630	H23	7,760	10,820
G13	6,510	9,430	W06	6,630	8,980	H24	7,440	10,380
G14	6,280	9,100						
G15	5,390	7,810						

Table IV-2.--Adjusted modulus of rupture (MOR) and clear wood stress (CWS) values for glued, laminated beams--continued

Beam identification	Adjusted MOR[1/]	Calculated CWS	Beam identification	Adjusted MOR[1/]	Calculated CWS	Beam identification	Adjusted MOR[1/]	Calculated CWS
	Lb/in.^{2}	Lb/in.^{2}		Lb/in.^{2}	Lb/in.^{2}		Lb/in.^{2}	Lb/in.^{2}
E-RATED HEM-FIR (1.8E TENSION LAMINATION)			E-RATED HEM-FIR (1.8E TENSION LAMINATION)--continued			E-RATED HEM-FIR (1.8E TENSION LAMINATION)--continued		
H25	5,680	8,560	H27	4,420	6,670	H29	4,770	7,190
H26	5,680	8,570	H28	6,740	10,160	H30	6,580	9,920
E-RATED "WHITE WOODS" (2.4E TENSION LAMINATION)			E-RATED "WHITE WOODS" (2.2E TENSION LAMINATION)					
9A	7,210	10,150	7A	7,180	11,170			
9B	6,360	8,950	7B	9,090	14,140			
11A	6,180	8,710	12A	8,250	12,830			
11B	9,270	13,060	12B	4,850	7,550			
E-RATED "WHITE WOODS" (2.0E TENSION LAMINATION)			E-RATED "WHITE WOODS" (2.0E TENSION LAMINATION)--continued			E-RATED "WHITE WOODS" (2.0E TENSION LAMINATION)--continued		
3A	9,270	13,830	A5	7,320	10,750	D1	7,970	10,410
3B	6,970	10,400	A7	10,240	15,030	D3	8,330	10,870
4A	7,460	11,140	A8	6,220	9,130	D4	7,820	10,210
4B	8,700	12,980				D5	7,140	9,330
			B1	6,820	10,010	D6	6,780	8,850
8A	6,610	9,510	B2	4,500	6,600	D7	6,280	8,200
8B	5,150	7,420	B3	6,860	10,070	D8	7,380	9,630
10A	6,640	9,550	B4	6,230	9,140			
10B	8,660	12,460	B5	6,760	9,930	E2	6,680	8,900
			B7	5,620	8,260	E4	7,290	9,710
A1	9,260	13,590	B8	7,750	11,380	E5	8,530	11,360
A2	7,640	11,210				E6	7,520	10,010
A3	9,350	13,720				E7	6,280	8,360
A4	8,690	12,760				E8	8,390	11,170
E-RATED "WHITE WOODS" (1.8E TENSION LAMINATION)			E-RATED "WHITE WOODS" (1.8E TENSION LAMINATION)--continued			E-RATED "WHITE WOODS" (1.8E TENSION LAMINATION)--continued		
H01	7,330	13,500	H11	5,750	10,580	1A	8,360	7,580
H02	6,220	11,460	H12	6,150	11,330	1B	7,760	11,180
H03	4,520	8,320	H13	4,080	7,520	2A	5,270	15,220
H04	5,320	9,790	H14	4,120	7,590	2B	6,540	11,510
H05	5,310	9,770	H15	4,640	8,540	5A	4,470	14,170
H06	4,480	8,240				5B	6,600	13,160
H07	5,150	9,480	LP31	5,810	9,690	6A	8,980	8,930
H08	4,200	7,730	LP32	5,230	8,710	6B	6,790	11,080
H09	4,280	7,870	LP33	4,980	8,300			
H10	4,380	8,070	LP34	4,470	7,450			
			LP35	4,250	7,090			
			LP36	5,500	9,160			
E-RATED "WHITE WOODS" (1.6E TENSION LAMINATION)			E-RATED "WHITE WOODS" (1.6E TENSION LAMINATION)--continued			E-RATED "WHITE WOODS" (1.6E TENSION LAMINATION)--continued		
LP37	4,370	7,960	LP39	4,940	9,000	LP41	4,580	8,350
LP38	3,920	7,150	LP40	4,470	8,140	LP42	3,580	6,520

1/ Adjusted to a 12-in.-deep, uniformly loaded beam with a 21:1 span-to-depth ratio and to 12 pct moisture content. Dead-load stresses of beam during test also added.

Table IV-3.--Summary of clear wood stress (CWS) analysis

Group description	Number of beams	Average CWS	Standard deviation	Coefficient of variation
		Lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}
Dense visual grade				
Douglas-fir	88	8,760	1,300	14.8
Southern pine	28	10,790	1,860	17.2
Hem-fir	30	8,980	1,290	14.4
E-rated grade				
2.4E + 2.6E Douglas-fir	17	10,590	1,700	16.1
2.2E Douglas-fir	21	9,660	1,530	15.8
2.2E Southern pine	6	10,410	1,390	13.4
2.0E Southern pine	21	9,850	1,560	15.8
2.0E Hem-fir	39	9,390	1,220	13.0
1.8E Hem-fir	6	8,510	1,400	16.5
2.4E White wood	4	10,220	2,000	19.6
2.2E White wood	4	11,420	2,850	25.0
2.0E White wood	35	10,450	1,910	18.3
1.8E White wood	29	9,760	2,200	22.5
1.6E White wood	6	7,850	890	11.3

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Improved utilization of lumber in glued laminated beams, by Russell C. Moody, Madison, Wis., FPL, 1977. 49 p. (USDA For. Serv. Res. Pap. FPL 292)

To provide criteria for improving lumber utilization in glued laminated beams, 120 specimen beams were evaluated.

KEYWORDS: E-rated lumber, laminated beams, lumber grade, unsymmetric beam design, wane.

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